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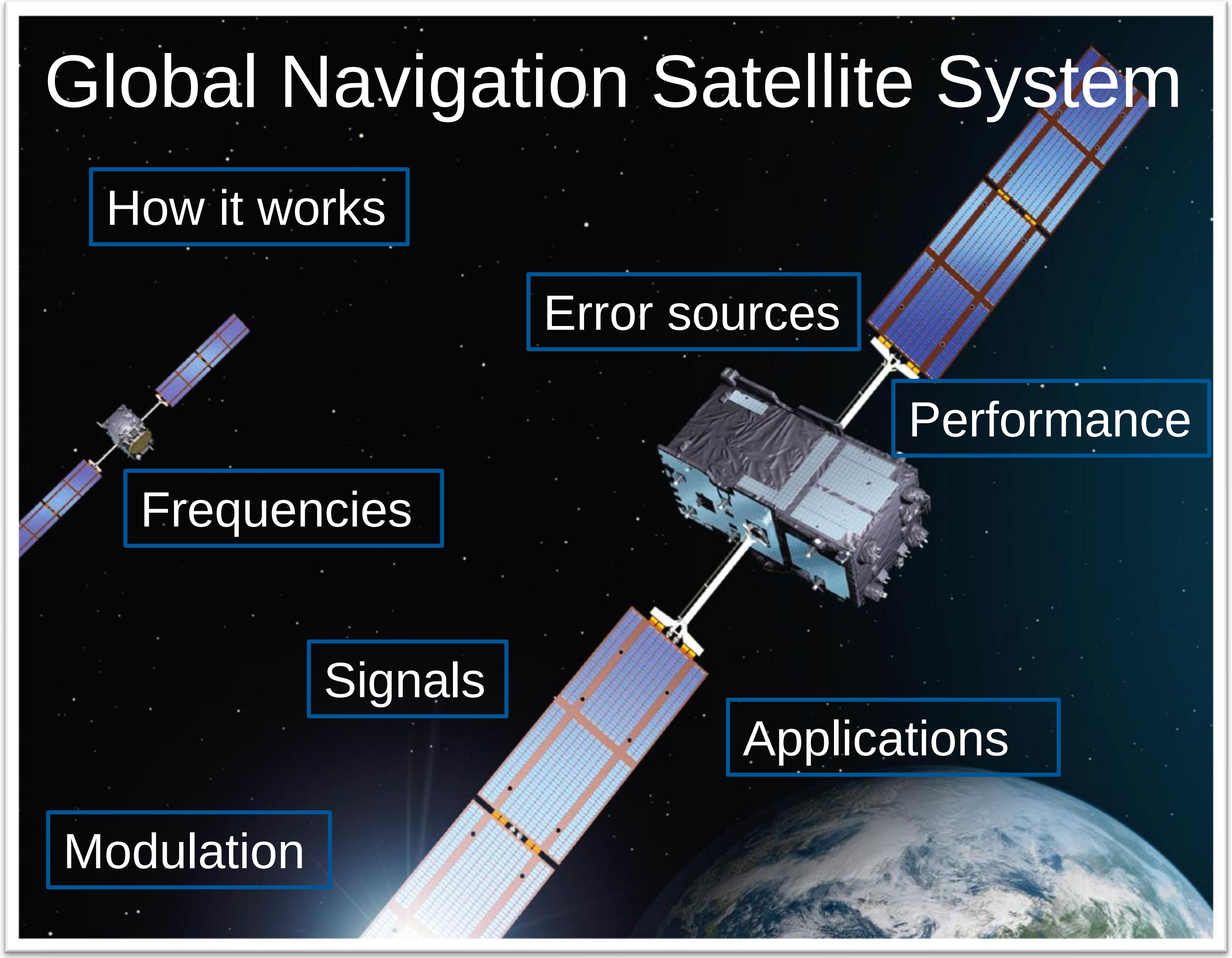
Introduction to GNSS Part 2

Dr Paul Blunt

GNSS



Global Navigation Satellite System
How it works
Error sources
Performance
Frequencies
Signals
Applications
Modulation

Part 2

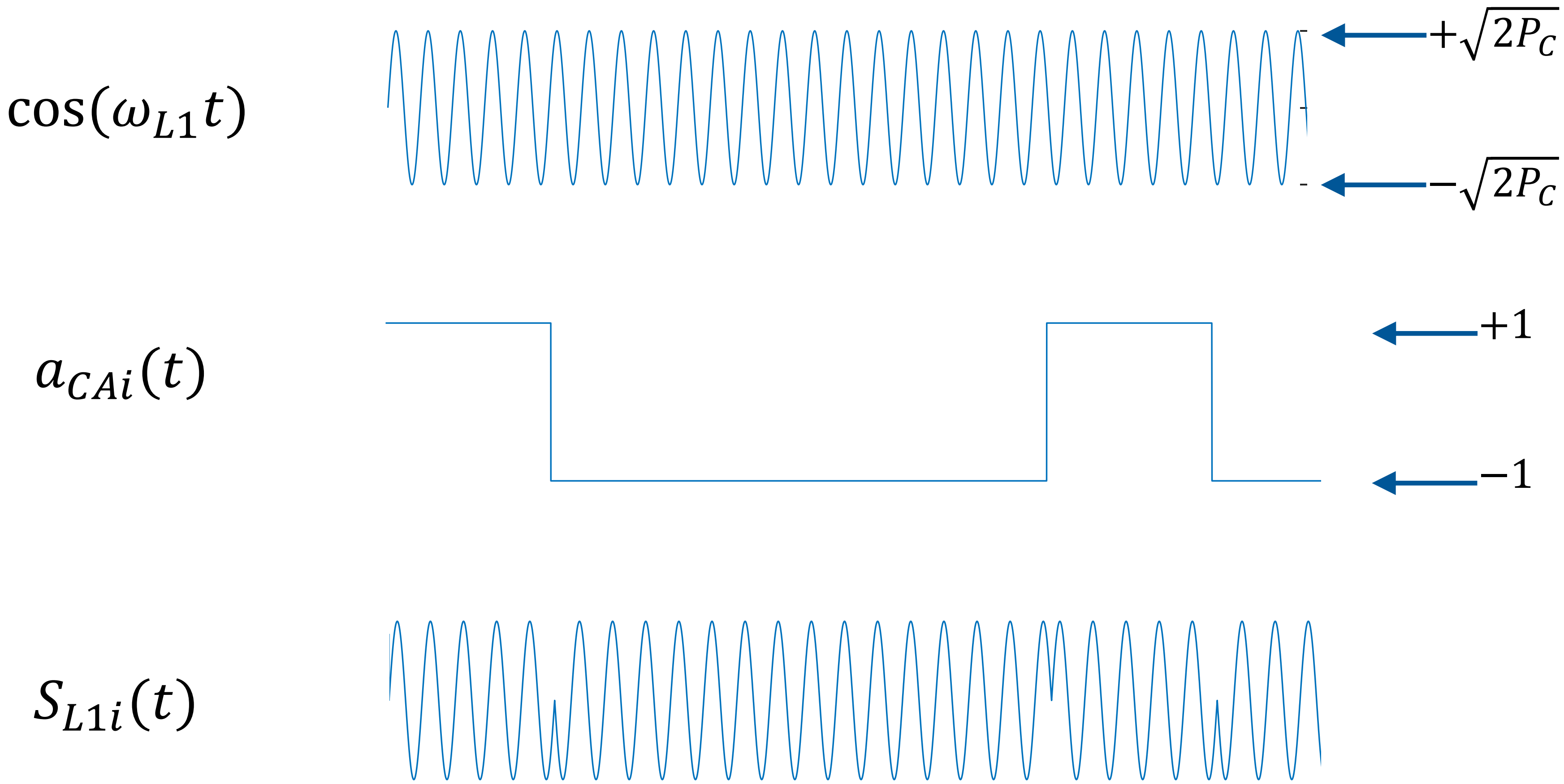
Signals

- BPSK and BOC modulation
- Navigation data structure
- Pilot Signals

GNSS receivers

- Hardware elements
- Processing
- Dual frequency and Differential receivers

GPS L1 C/A signal – BPSK(1)



GPS L1 C/A signal – BPSK(1)

L1 carrier, 1575.42 MHz

Navigation data, $\in (-1, +1)$
50 bps

$$S_{L1i}(t) = \sqrt{2P_C}\, d_i(t)\, a_{CAi}(t) \cos(\omega_{L1} t)$$

Amplitude

C/A PRN code, $\in (-1, +1)$,
1.023 Mcps,
1023 chips, 1ms long
BPSK(1)

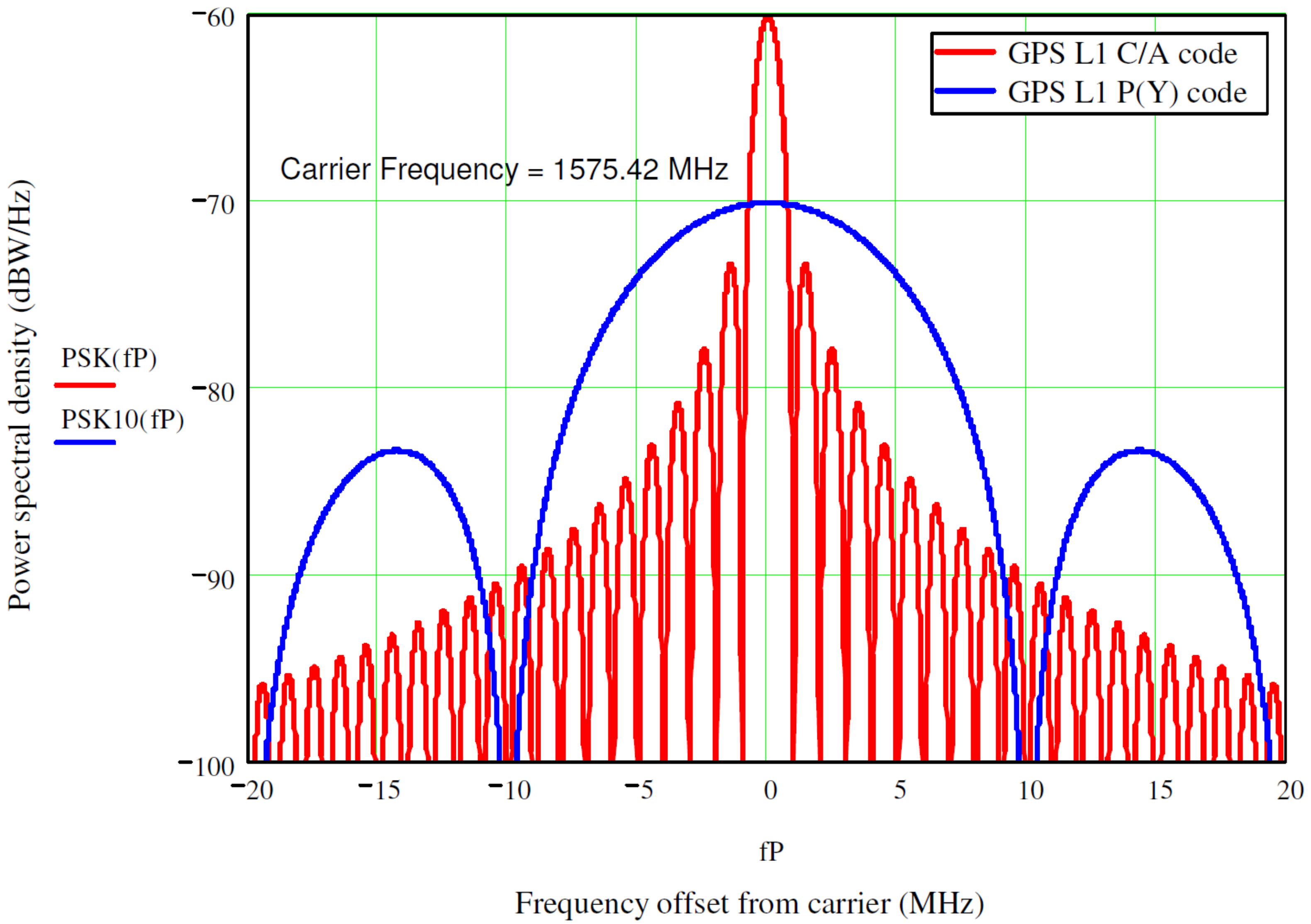
i – satellite number

Navigation data → Satellite locations

PRN code → Pseudorange

Carrier Doppler → Velocity

Frequency Spectrum



Spectrum follows sinc² shape

$$S_{PRN}(\omega) = A^2 T_C \mathrm{sinc}^2\left(\frac{\omega T_C}{2}\right)$$

$$\mathrm{sinc}(x) = \frac{\sin(x)}{x}$$

T_C - chip period

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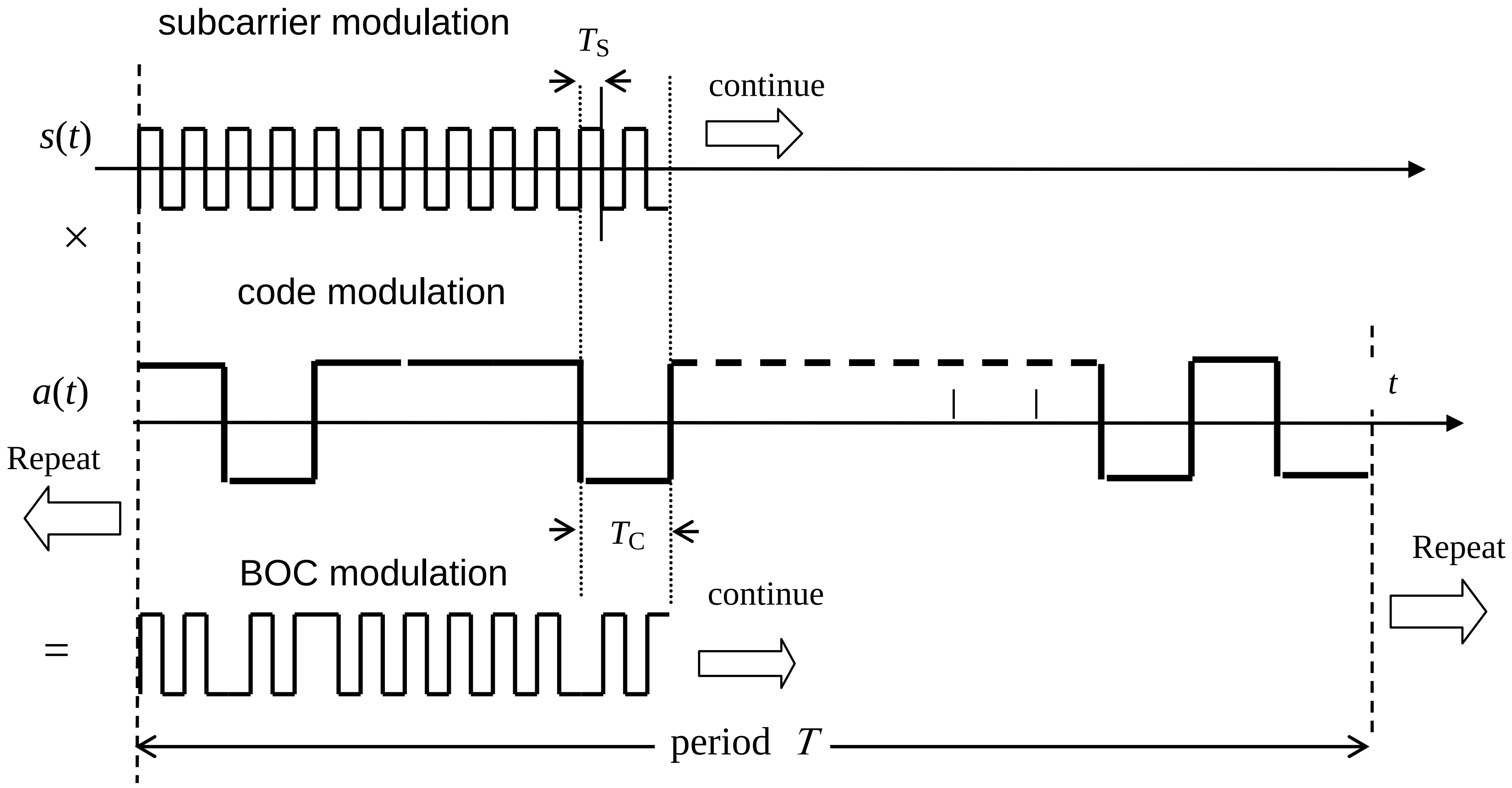
BOC modulation

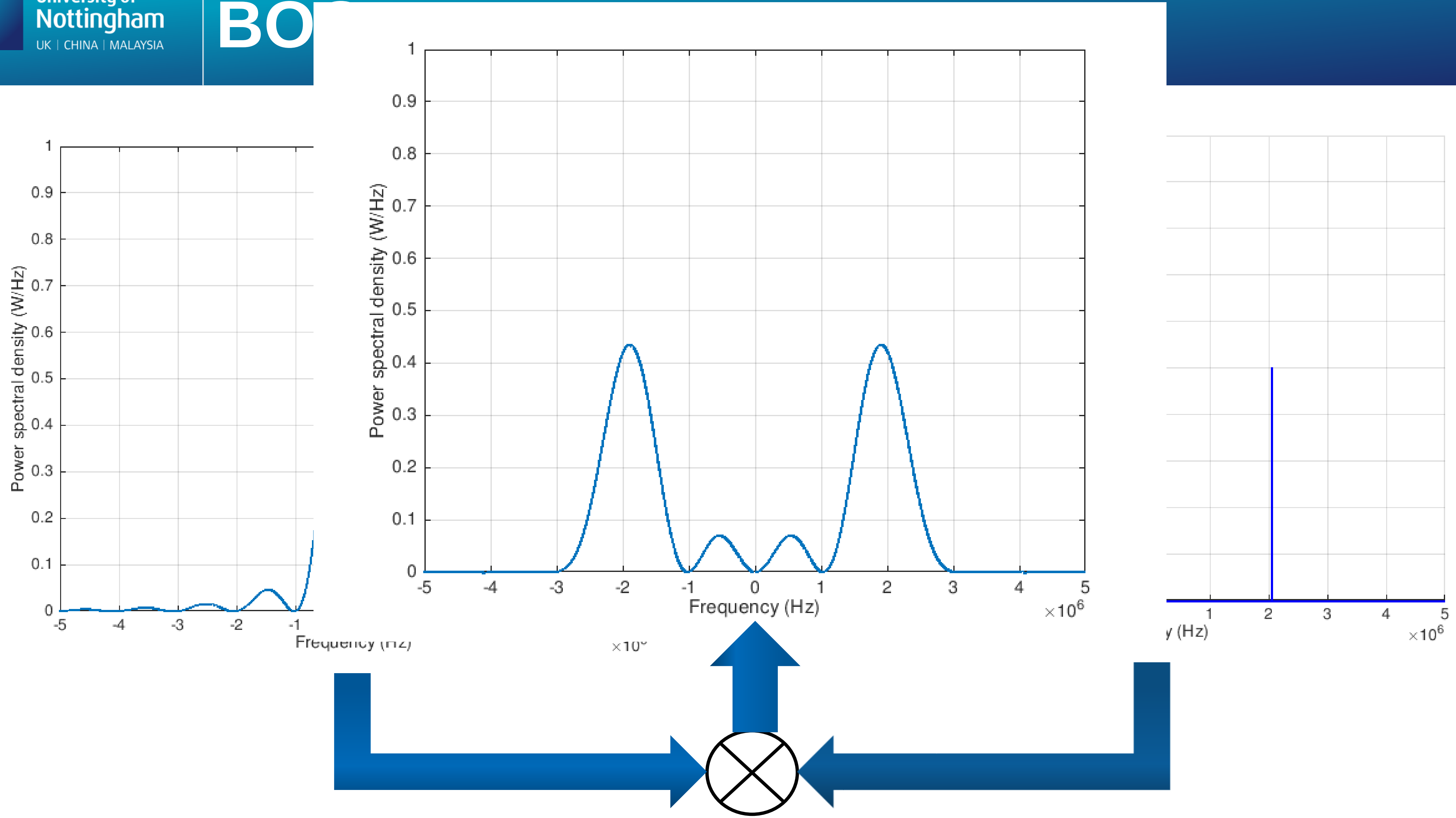
Binary Offset Carrier (BOC)

- Square wave sub-carrier modulation

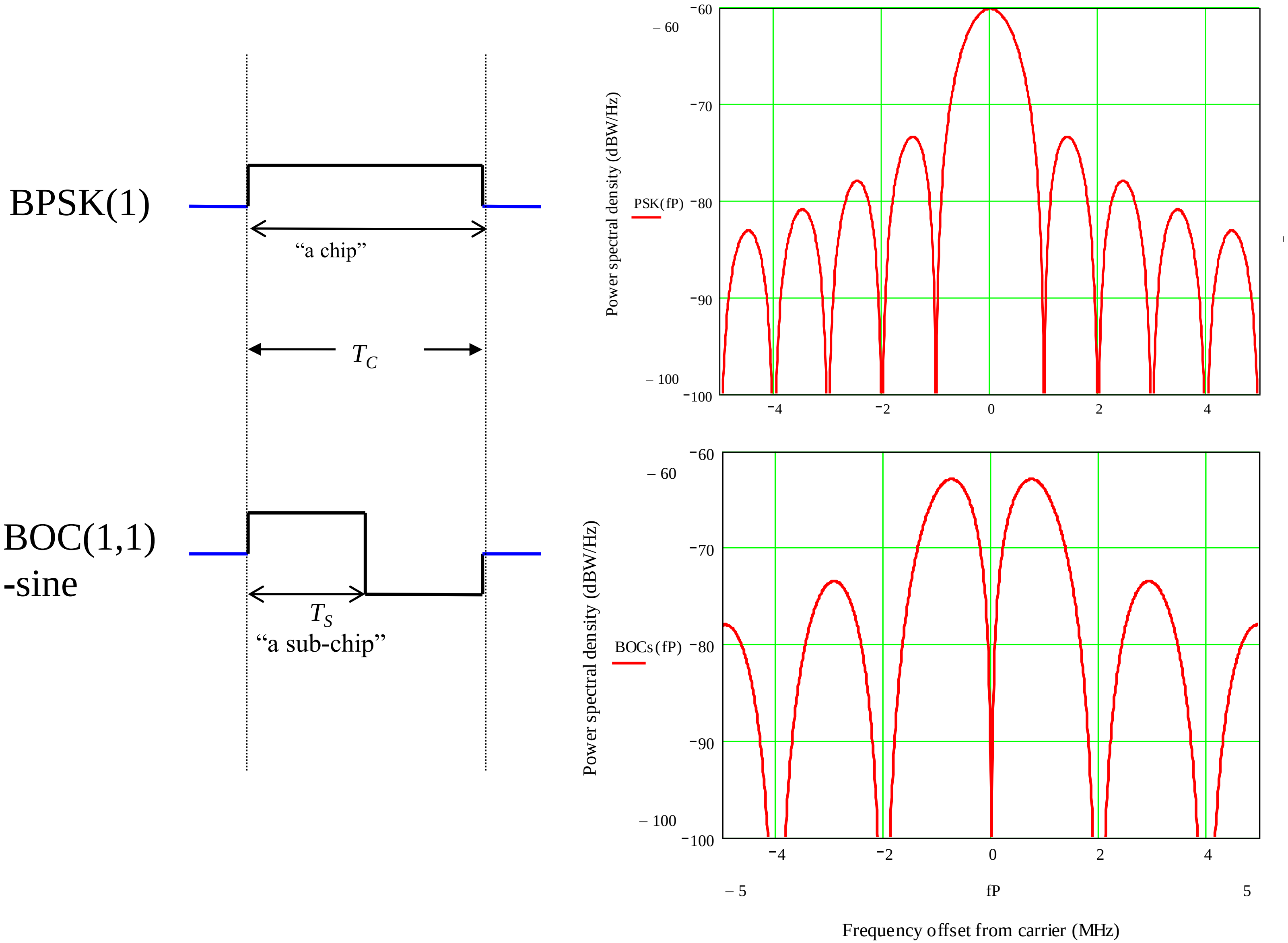


- BOC(m, n), m = subcarrier frequency, n = code rate, both integer multiples of 1.023 MHz

BO


Power spectral density (W/Hz)
Frequency (Hz)
$\times 10^6$
Power spectral density (W/Hz)
Frequency (Hz)
$\times 10^6$
y (Hz)
$\times 10^6$

Spectrums

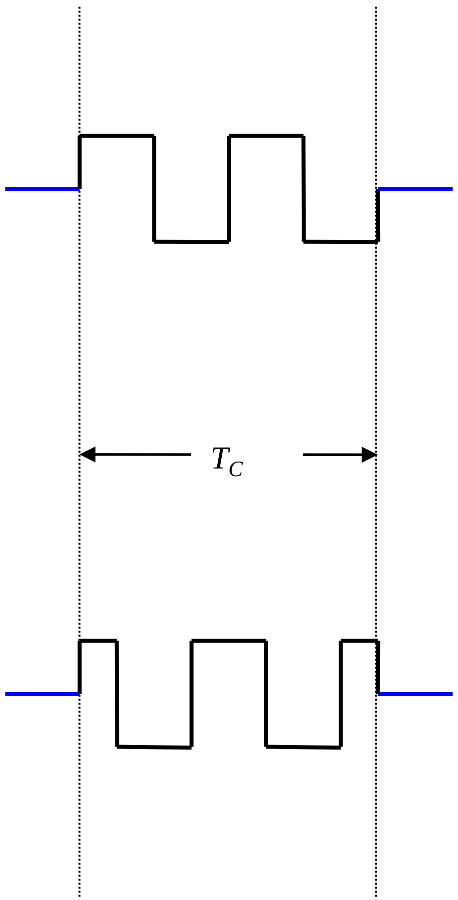


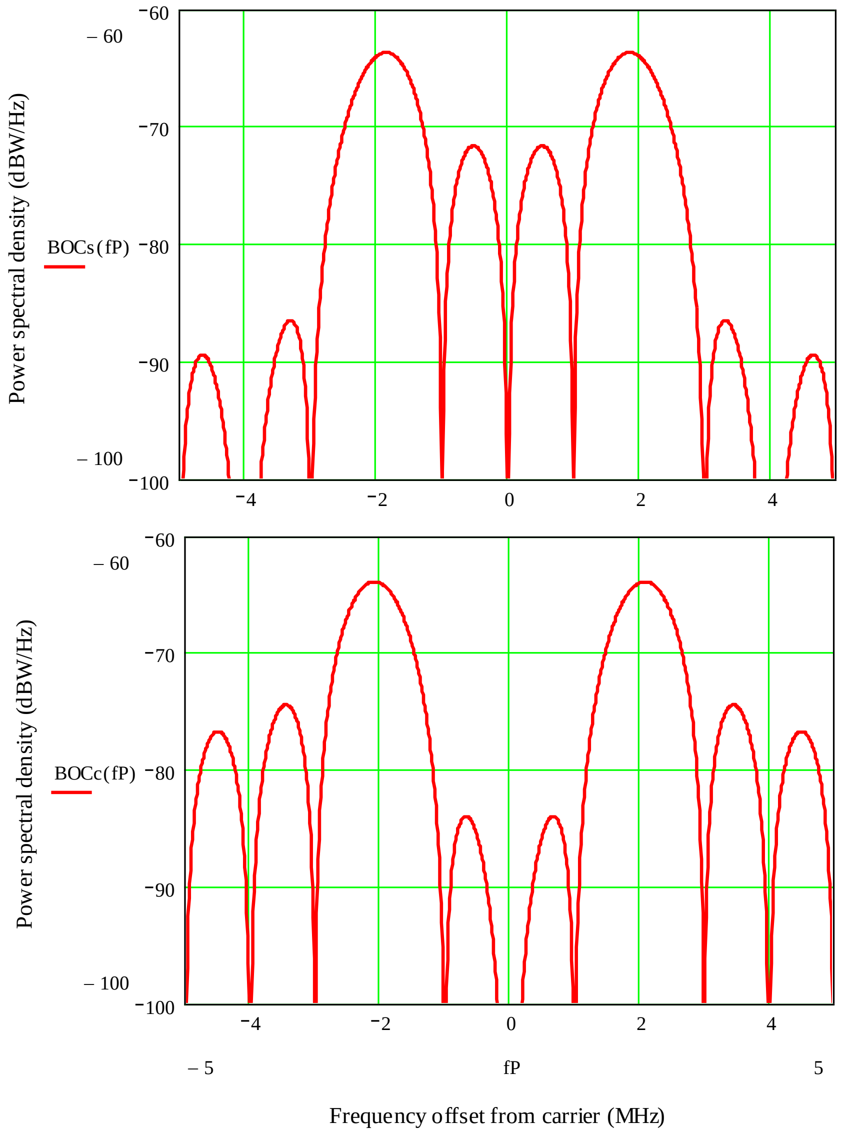
BPSK(1)
"a chip"
T_C
BOC(1,1) -sine
T_S
"a sub-chip"
Power spectral density (dBW/Hz)
PSK(fP)
BOCs(fP)
−60
−70
−80
−90
−100
−4
−2
0
2
4
−5
fP
5
Frequency offset from carrier (MHz)

Spectrums

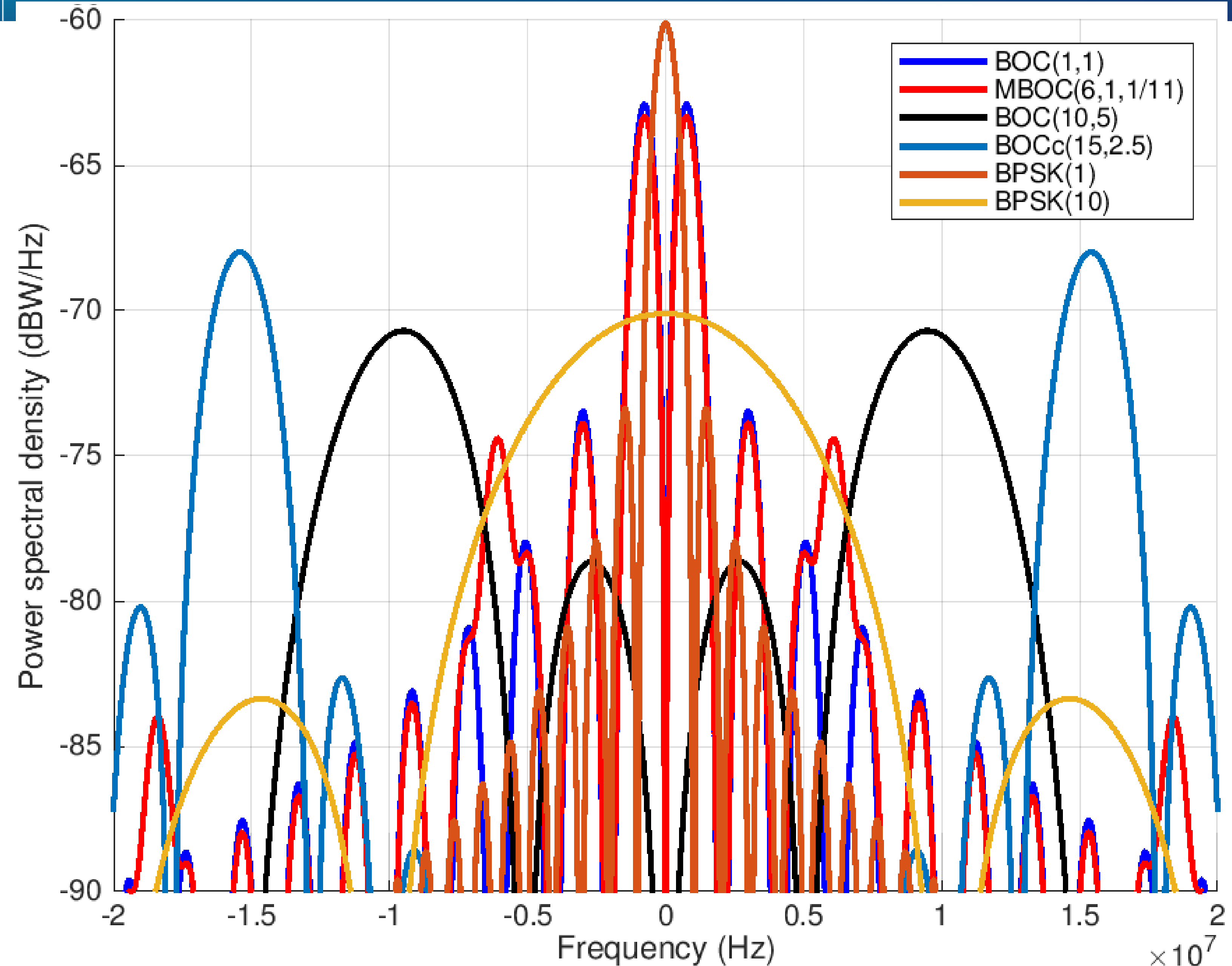
BOC(2,1)
-sine

BOC(2,1)
-cosine





Why? – spectral reuse / separation



L1 band

Why ?

What's the point in BOC ?

- Spectral separation
- Increased bandwidth → Improved timing accuracy
- Increased bandwidth → Improved multipath performance
- Carrier suppression

Any drawbacks ?

- Increased receiver complex in tracking (receiver cost and reliability)
- More complex acquisition (receiver cost)

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Navigation data

GPS NAV data

Each GPS satellite transmits the L1 C/A signal modulated with the ‘legacy’ NAV data containing

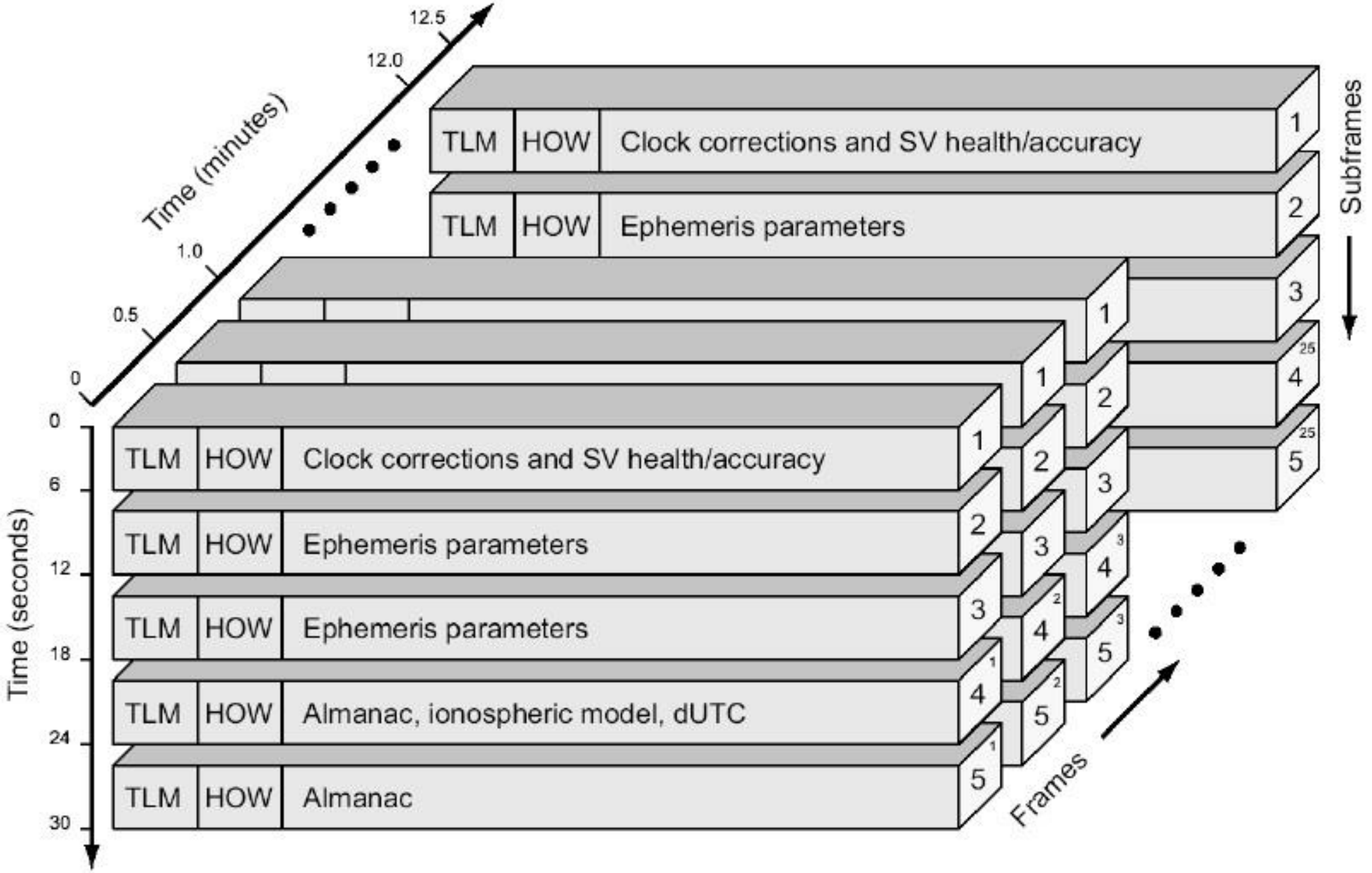
- **Almanac** (low precision orbital parameters) for all GPS satellites
- **Ephemeris** (high precision orbital parameters) for the transmitting satellite
- **GPS time** and satellite **clock correction** parameters
- Satellite **health** data

GPS NAV data

- **Data rate** = 50 Hz (bps), bit period = 20 ms
- **Word length** = 30 bits (0.6 seconds)
- **Subframe length** = 10 words, 300 bits (6 seconds)
- **Frame length** = 5 subframes, 50 words, 1500 bits (30 seconds)
- **Superframe** = 25 frames (12.5 minutes)

If starting with no help a receiver will need a Frame before it can use that satellite

GPS NAV data



[Borre *et al 2007]*

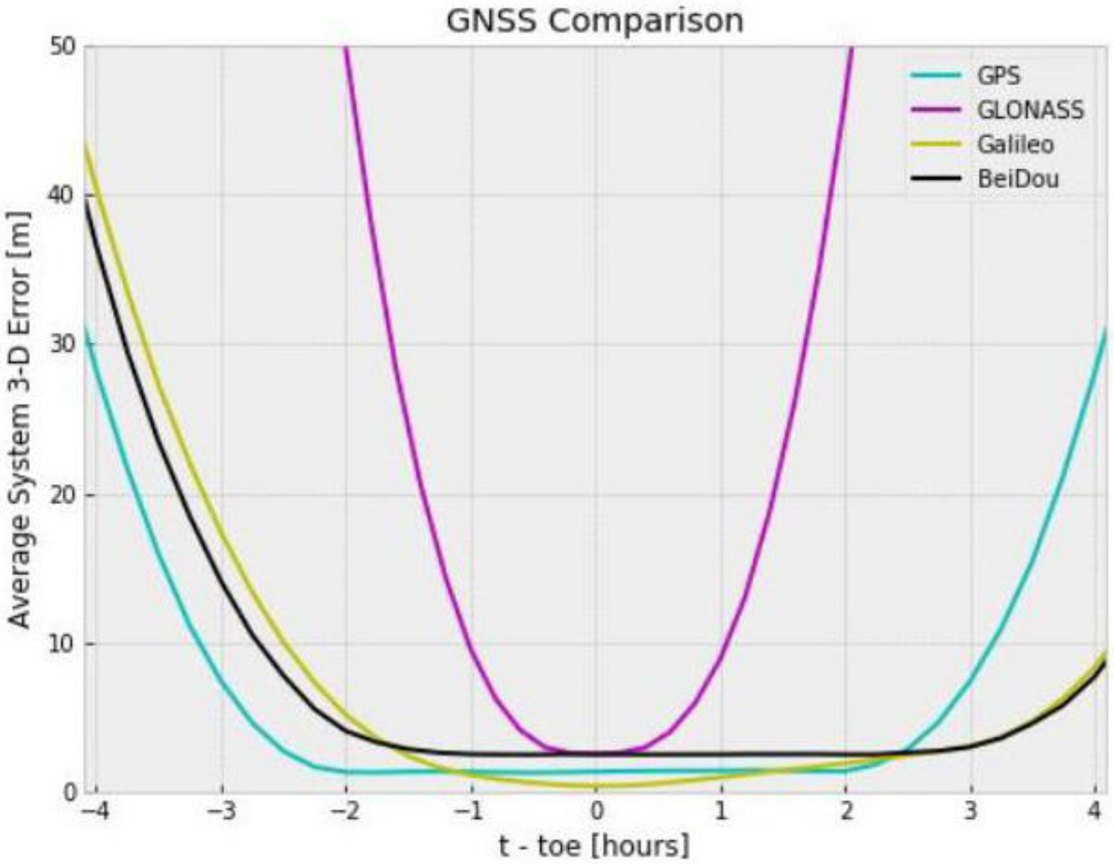
Navigation data effects acquisition times

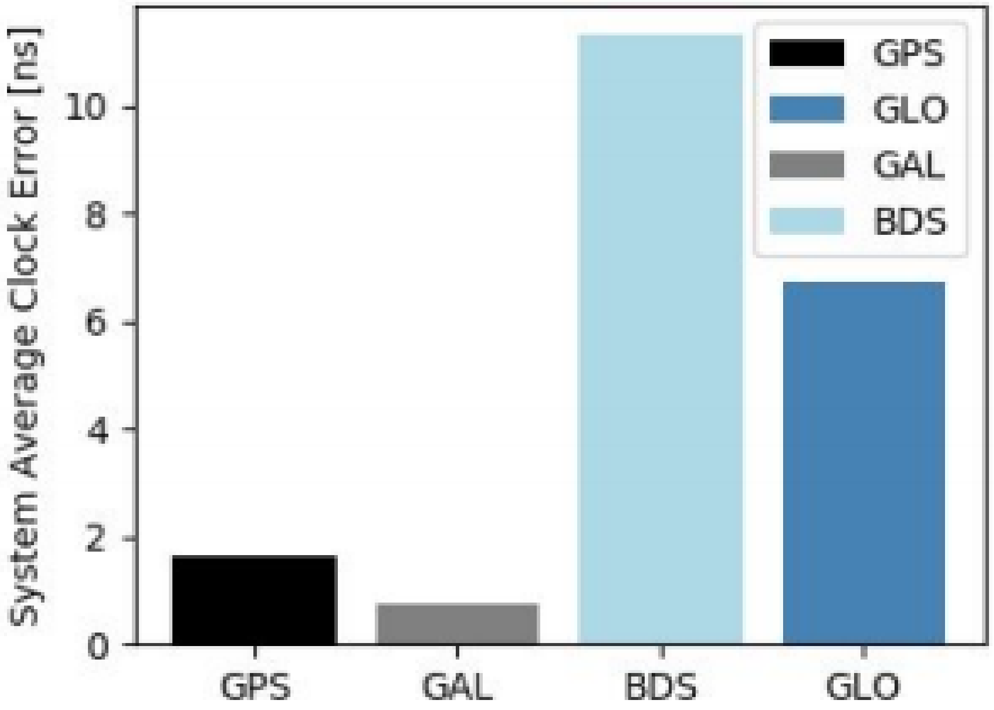
Receiver modes and time to usable signals

Cold start – No almanac, no ephemeris, no time, no position,
~45s to 120 seconds

Warm start – No ephemeris, Almanac, rough time and position (<100km)
~ 35 to 45s (time to read ephemeris)

Hot start – Ephemeris, Almanac, decent time and position (<1km)
~ 1s to 5s





Broadcast ephemeris error with age

Broadcast satellite clock errors

An Assessment of the Accuracy of Broadcast Ephemerides for Multi-GNSS Positioning," in *IGS Workshop*, Oct 29th - Nov 2nd, 2018

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Error Contributors to range measurements

Error source	Bias error	Random error	RSS
Satellite orbit (ephemeris)	0.8	0.1	0.81
Satellite clock	0.5	0.3	0.58
Ionosphere			
Troposphere			
Multipath	1.5	0.3	1.53
Receiver noise	0.2	0.5	0.54
Total range error			

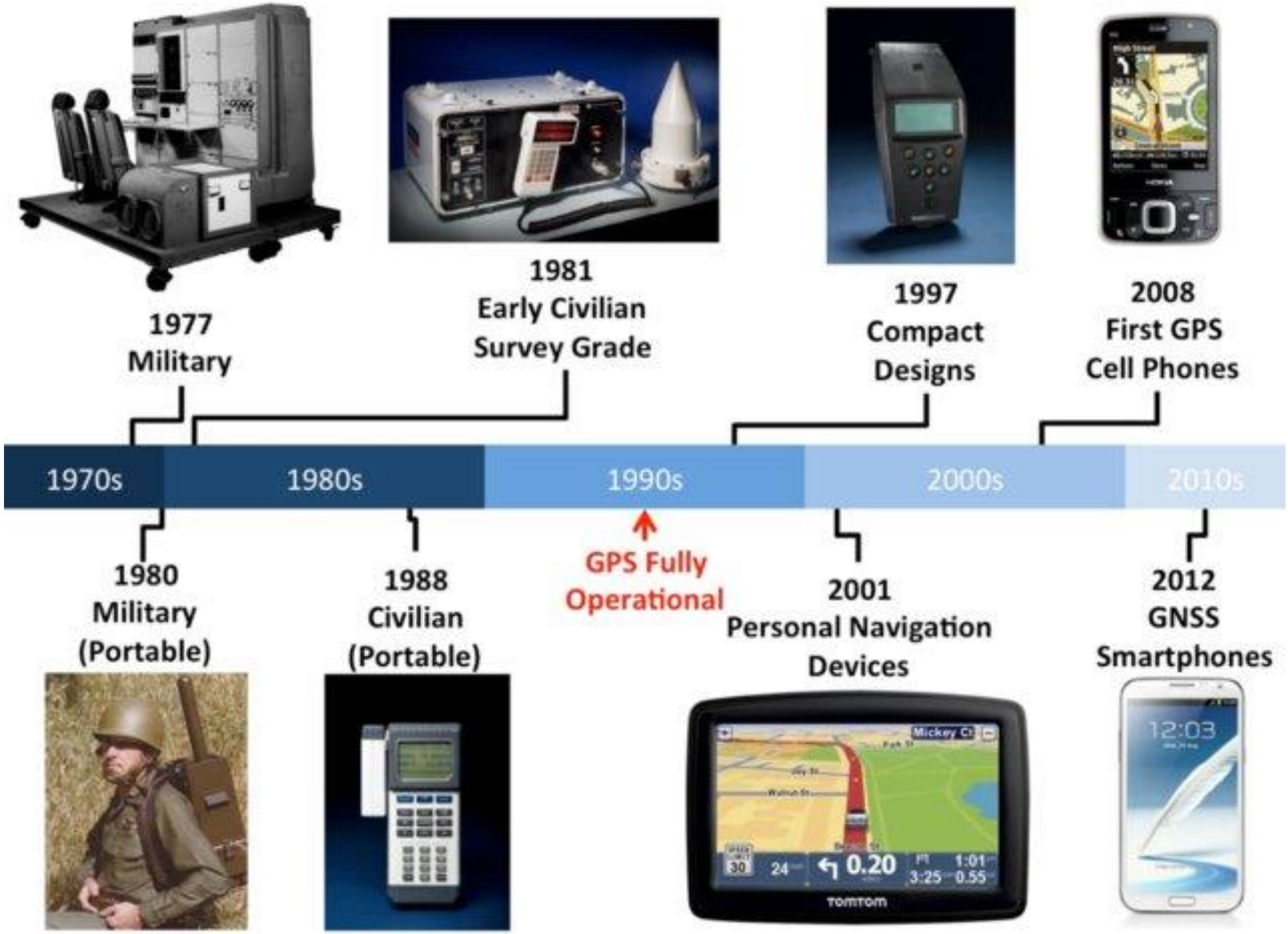
Some typical numbers

Pilot Signals

- Modernised GPS, Galileo and Beidou all have additional pilot signals
- **No data modulation** allows for longer averaging times
  - Limited to 20 ms in legacy GPS
- **Reduced** phase and frequency **jitter**
- **Lower** loss of lock threshold (improved resilience to interference)
- **Increased** pull-in **range & jerk tolerance**

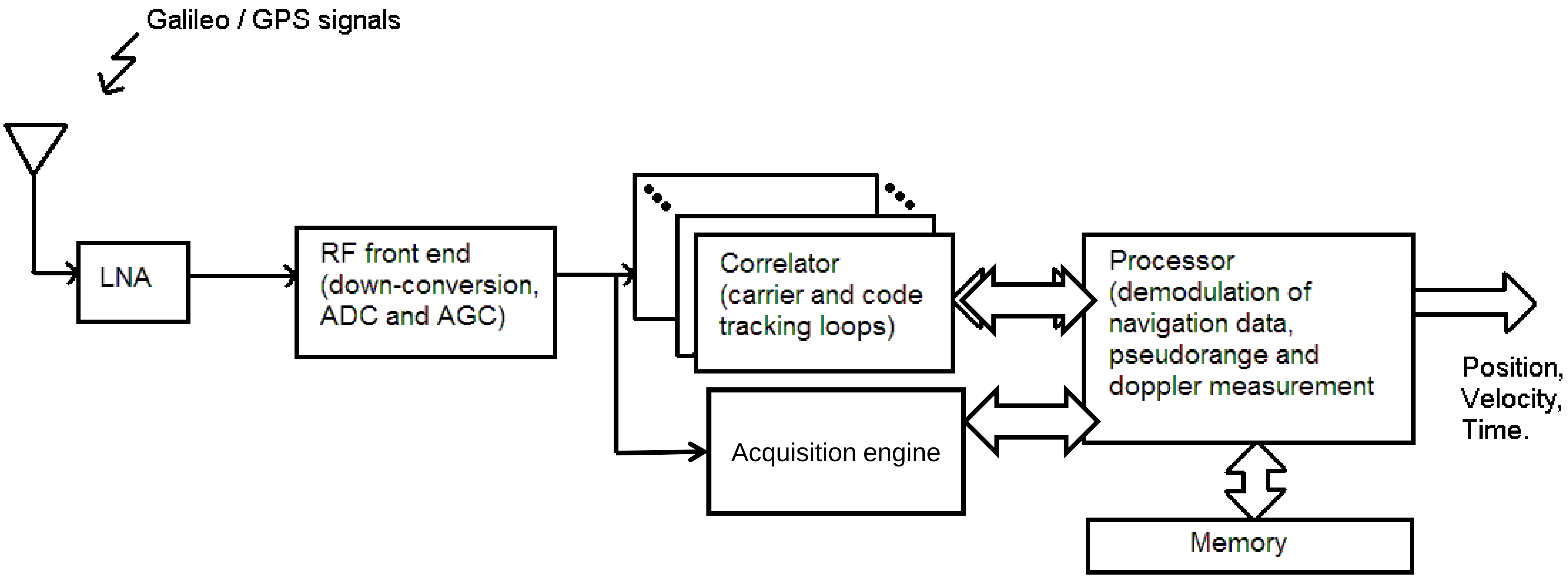
GNSS receivers

GNSS receivers through the years



[Tyler Reid 2017]

GNSS receiver overview



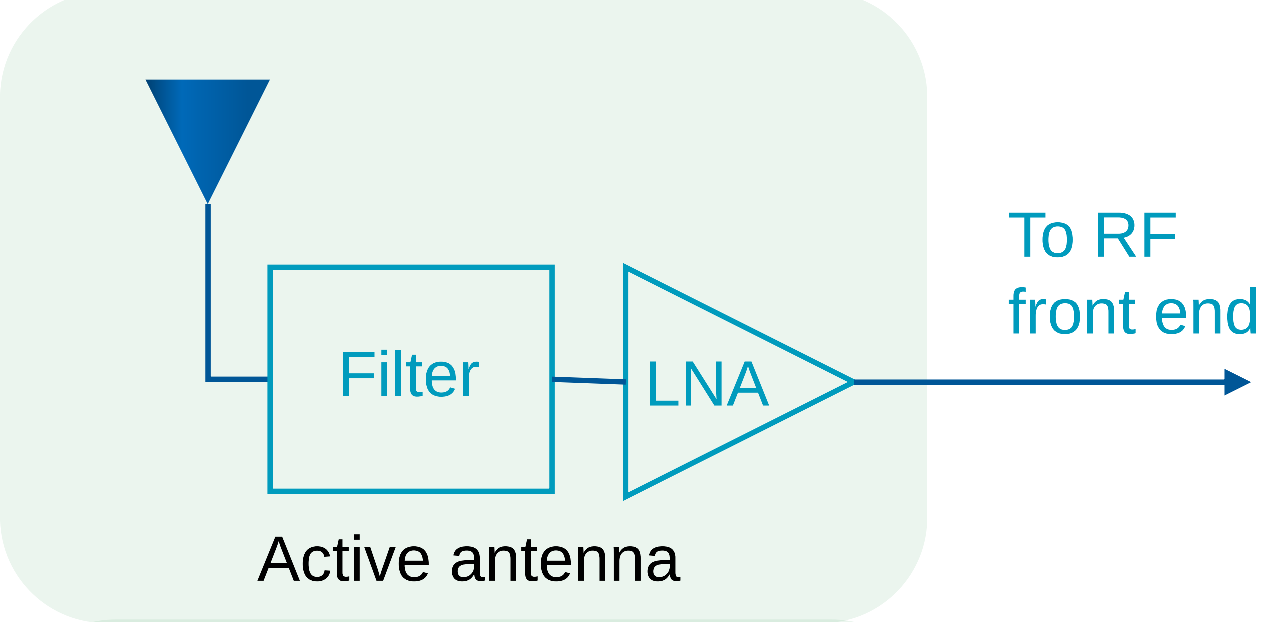
Antenna

Active

- Includes Low Noise Amplifier

+ Can enable the use of long cables
+ Sets system noise figure (reducing the effect of follow on stages)

- More hardware
  - ➢ LNA
  - ➢ Power supply + limit circuit

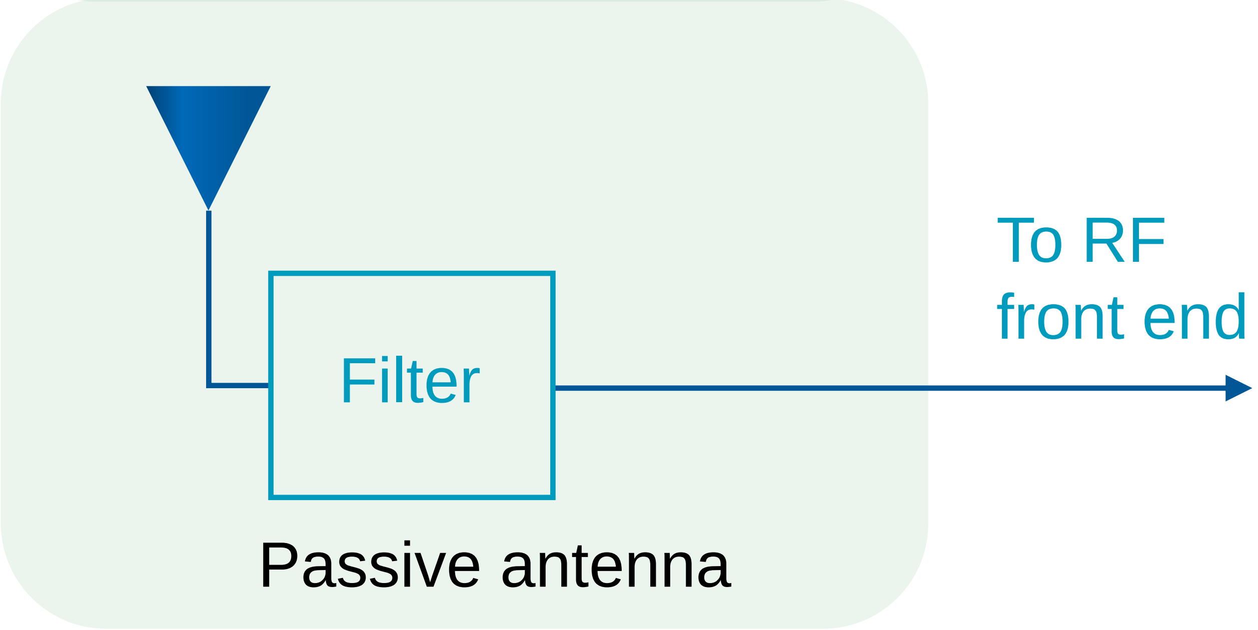


Passive

- No LNA

+ Reduced number of components
+ Simplified / robust design

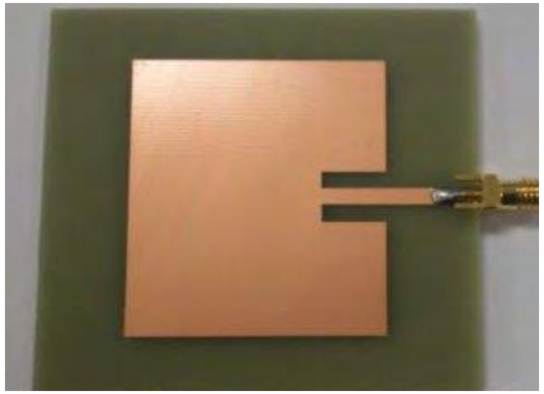
- Requires close integration
- Requires good RF system noise figure

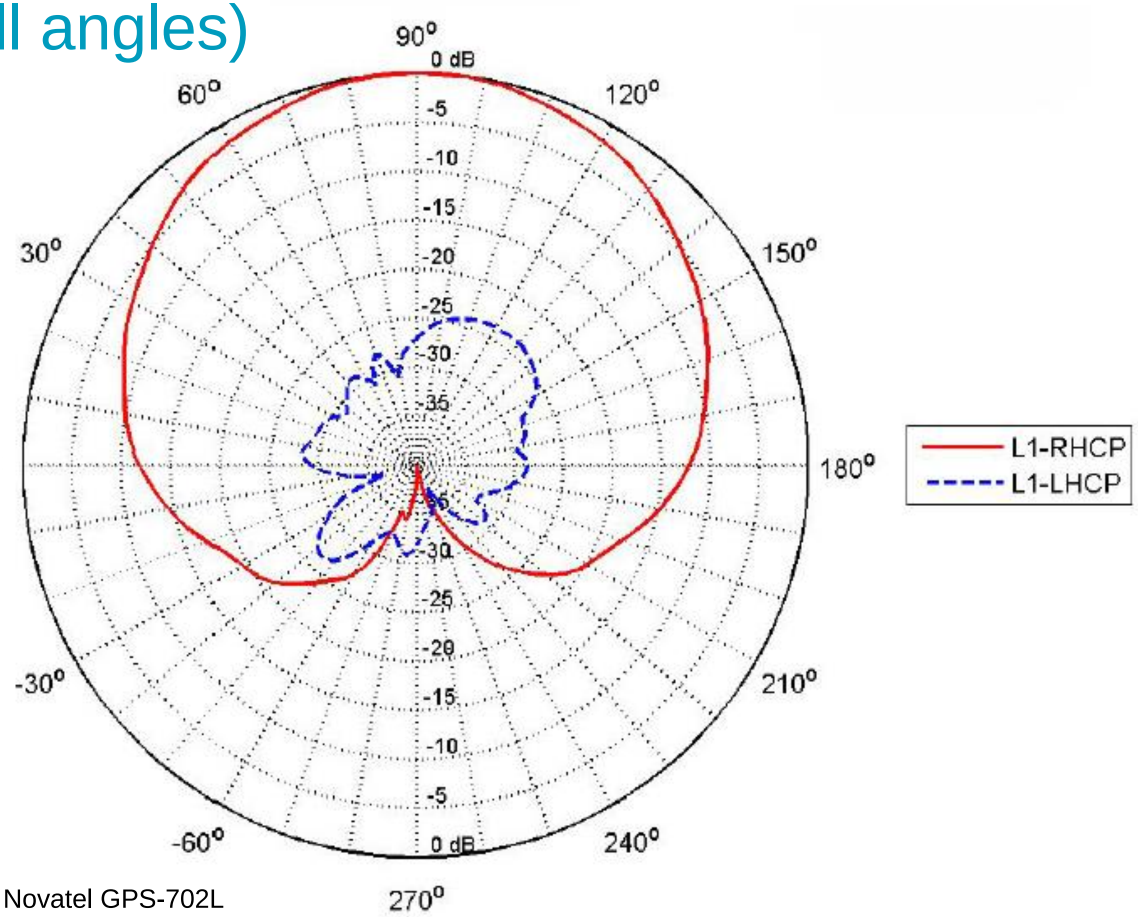


Antenna

Can take many different forms, basic requirements

- Support GNSS frequencies/Bandwidths
- Broad antenna gain pattern (sats from all angles)
- Circularly polarised

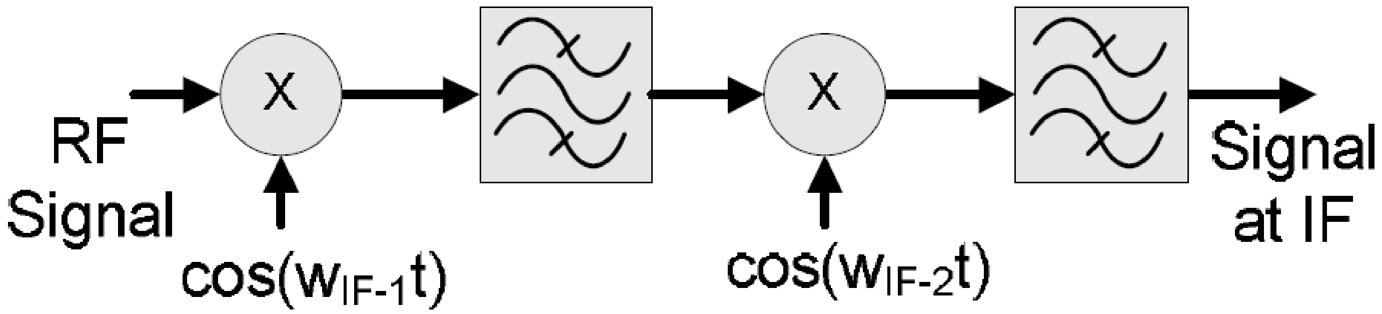




Novatel GPS-702L

RF front end

Heterodyne down-conversion

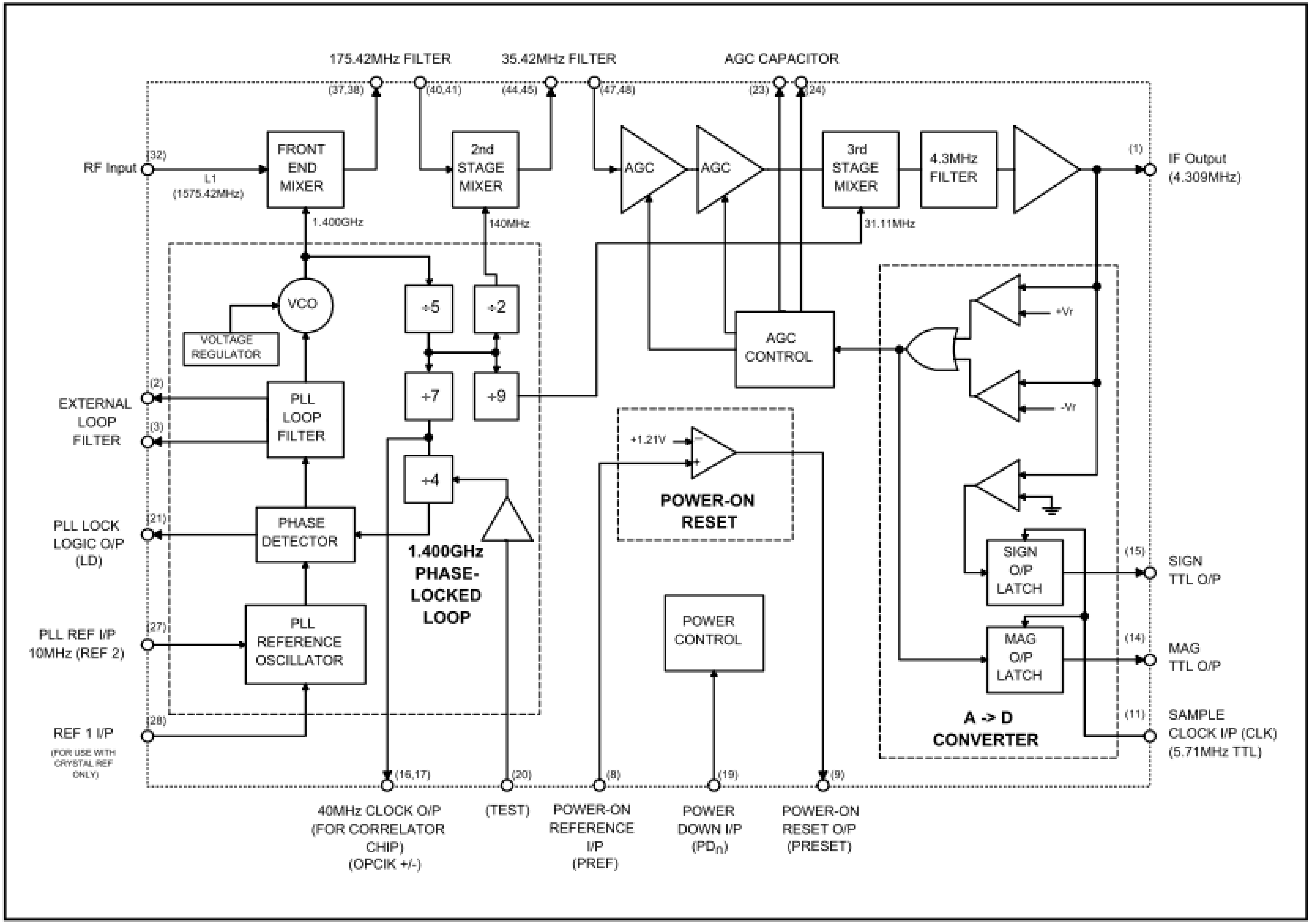


- Performed in a number of stages
- Uses band-pass filters at each stage

+ Good out of band rejection
+ Isolation of mixing frequencies from the RF
- Uses many components

Heterodyne down-conversion

Zarlink GP2015

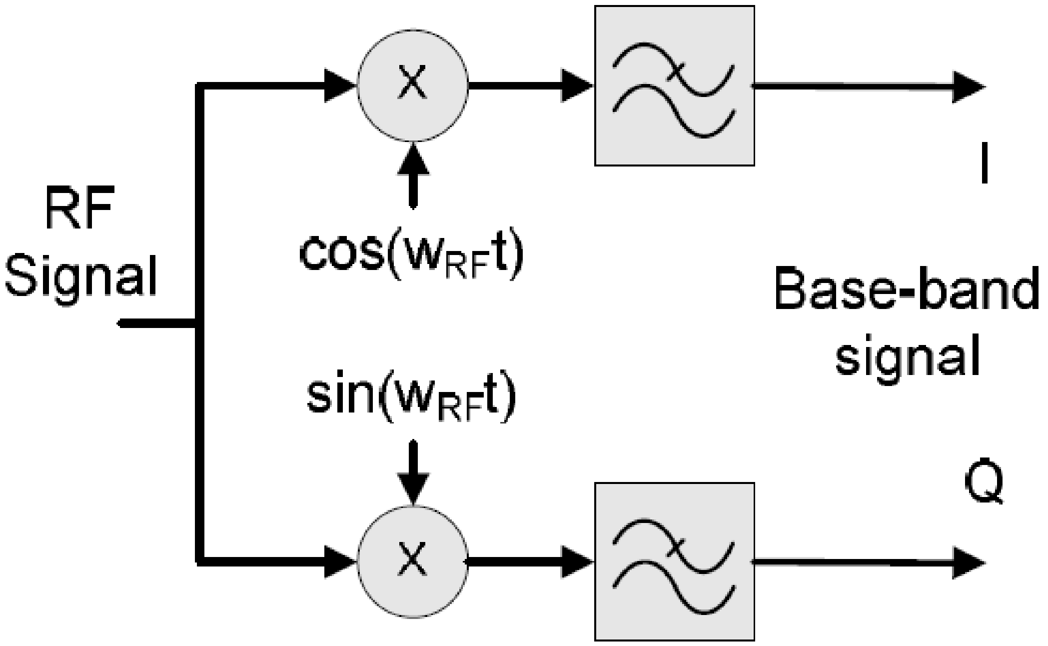


RF front end

Homodyne down-conversion

- Direct conversion to baseband from RF

\+ Single stage mixer
\+ Simple low pass filter
\- Risk of self interference, I/Q mismatch, DC noise
\- DC filter can degrade BPSK signals, BOC is immune
\- Requires image reject mixer (complex mixer) at baseband
  - generally performed in digital domain

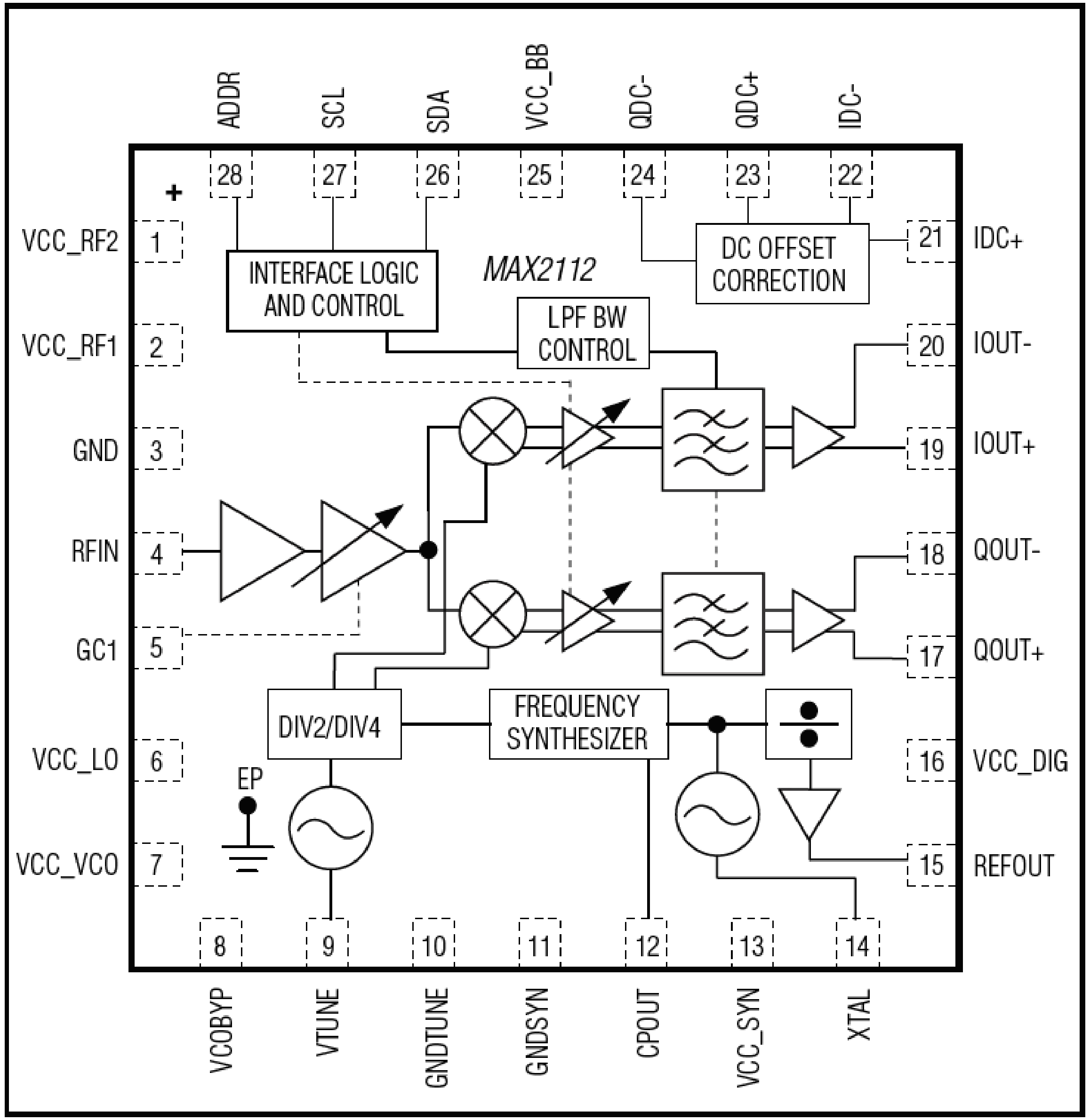


Homodyne down-conversion

MAXIM 2112 – direct conversion tuner

925 to 2175 MHz mixer range

Up to 80 MHz two sided bandwidth



Oscillator

Stability

- Tuning and temperature – 1 ppm is 1.57542 kHz offset at L1 (300 m/s)

Phase noise

- close in, 1Hz important for tracking loop jitter

Vibration/shock sensitivity

- Causes cycle slips and loss of lock

Smooth response

- Temperature or drive level can causes frequency jumps, ‘activity dips’

Crystal (XTAL) – mass-market only, ~ 50 µW, ±30 ppm
TCXO – Suitable for precise positioning/timing, ~10 mW, ±0.5 to 5 ppm
OCXO – Best stability and hold-over, bulky, ~ 0.5 W, ±25 to 500 ppb

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GNSS receivers

Signal processing

Acquisition

- Often a **single unit** used for all satellites sequentially
- Detection and **coarse** estimation of received signal
  - Carrier **Doppler**
  - PRN code **delay**

Tracking

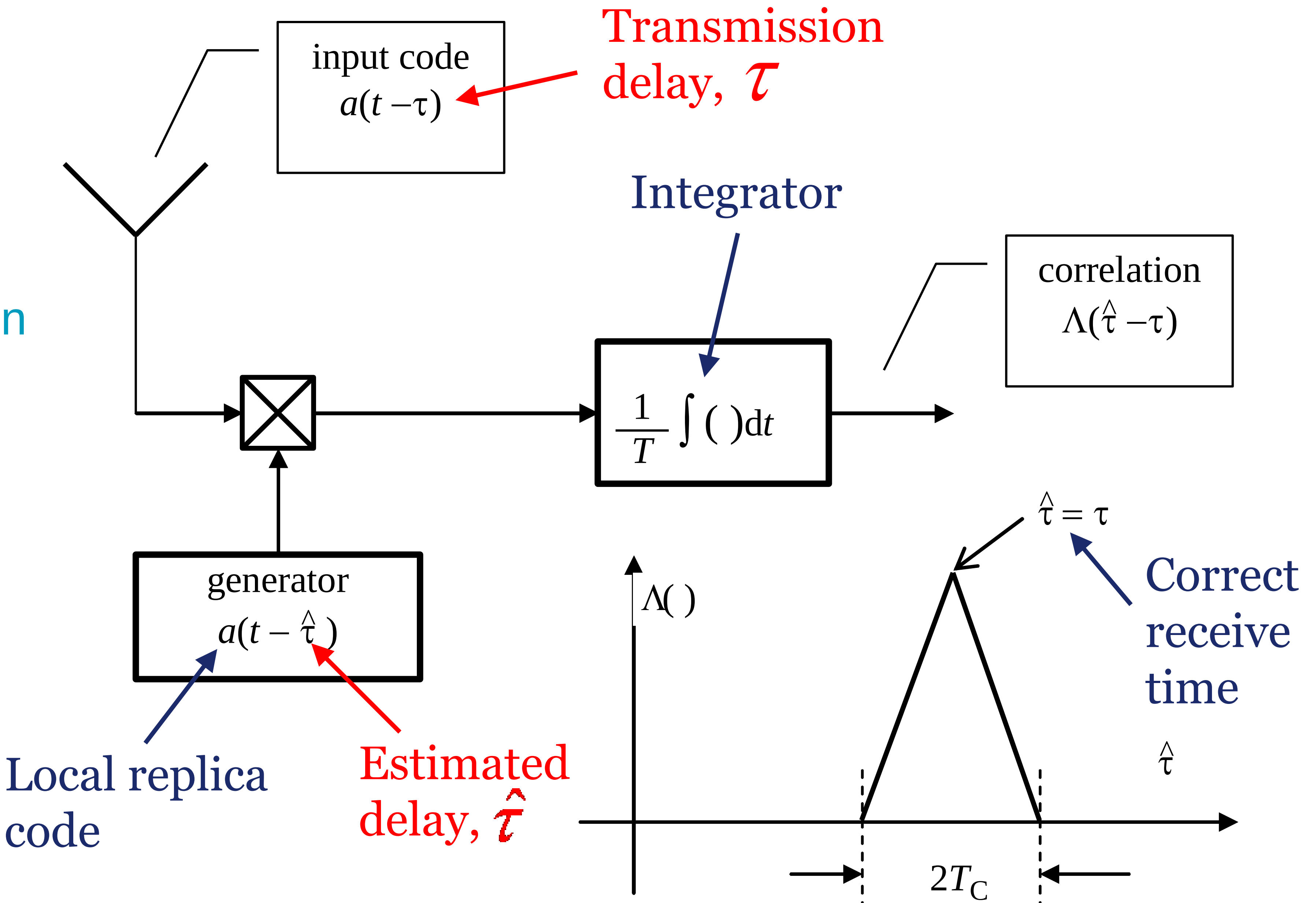
- **Multiple** parallel **channels** – 12 per signal component per constellation per frequency (hundreds of channels)

- Refined **Pseudorange** (delay), **pseudorange rate** (Doppler) estimates

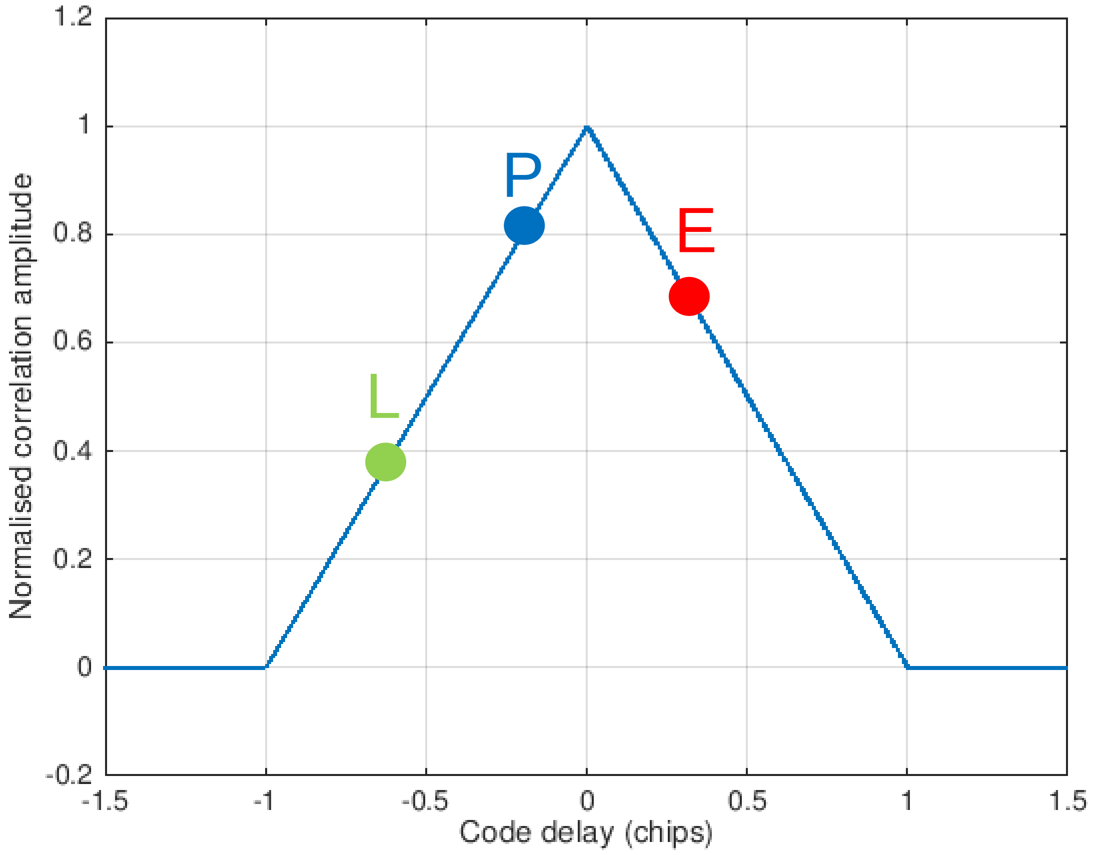
- **Decoding** of navigation **data symbols**

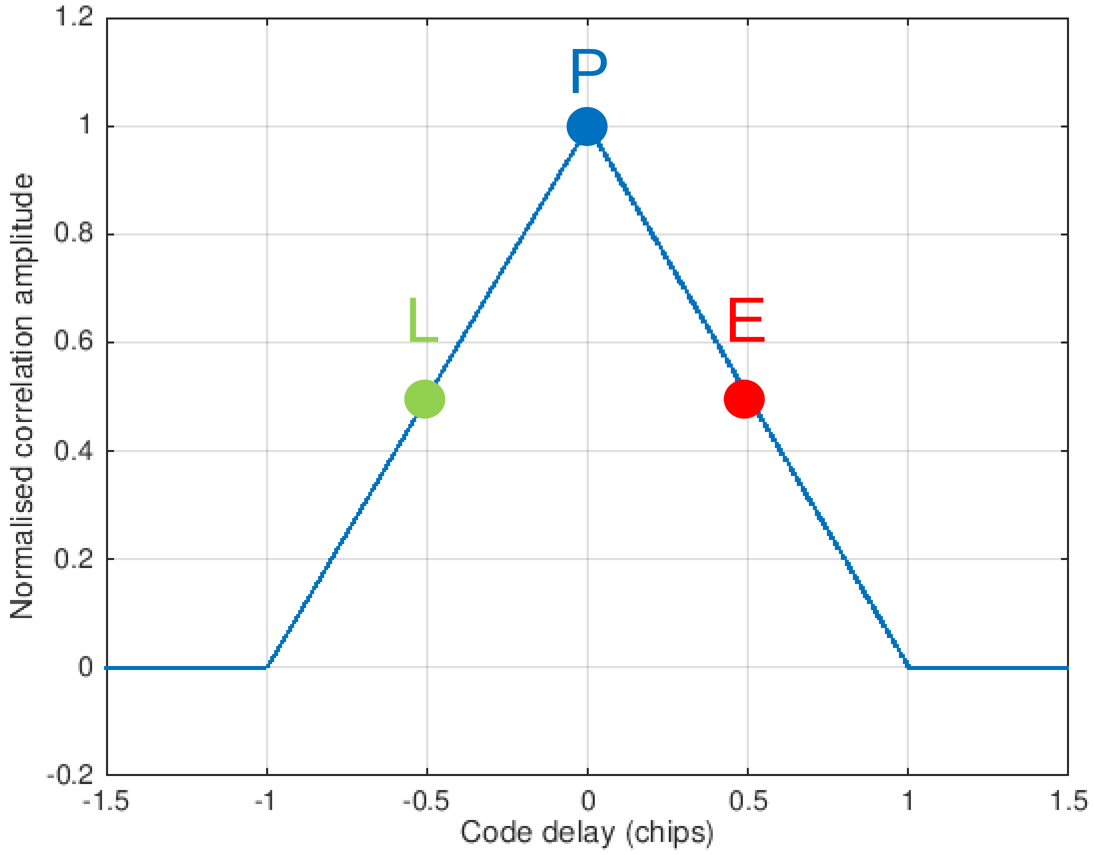
Code reception

Ignoring Carrier modulation for now



Code tracking





Received BPSK signal

$S_{L1}(t) = \sqrt{2P_C}d(t)a(t)\cos(\omega_{L1}t)$

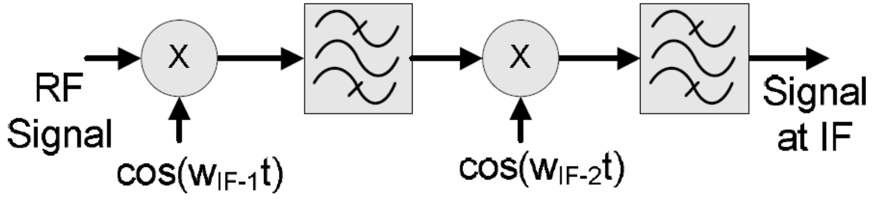
The aim of receiver is to find

- Code delay, τ
- Carrier Doppler, ω_D
- Carrier Phase, φ_R

$S_{RF}(t) = \sqrt{2P_R}d(t-\tau)a(t-\tau)cos\big((\omega_{L1}+\omega_D)t+\varphi_R\big)$

Ignoring noise + interference

$S_{IF}(t) = \sqrt{C}d(t-\tau)a(t-\tau)cos\big((\omega_{IF}+\omega_D)t+\varphi_{IF}\big)$



RF front end

Acquisition and tracking processing

Doppler shift

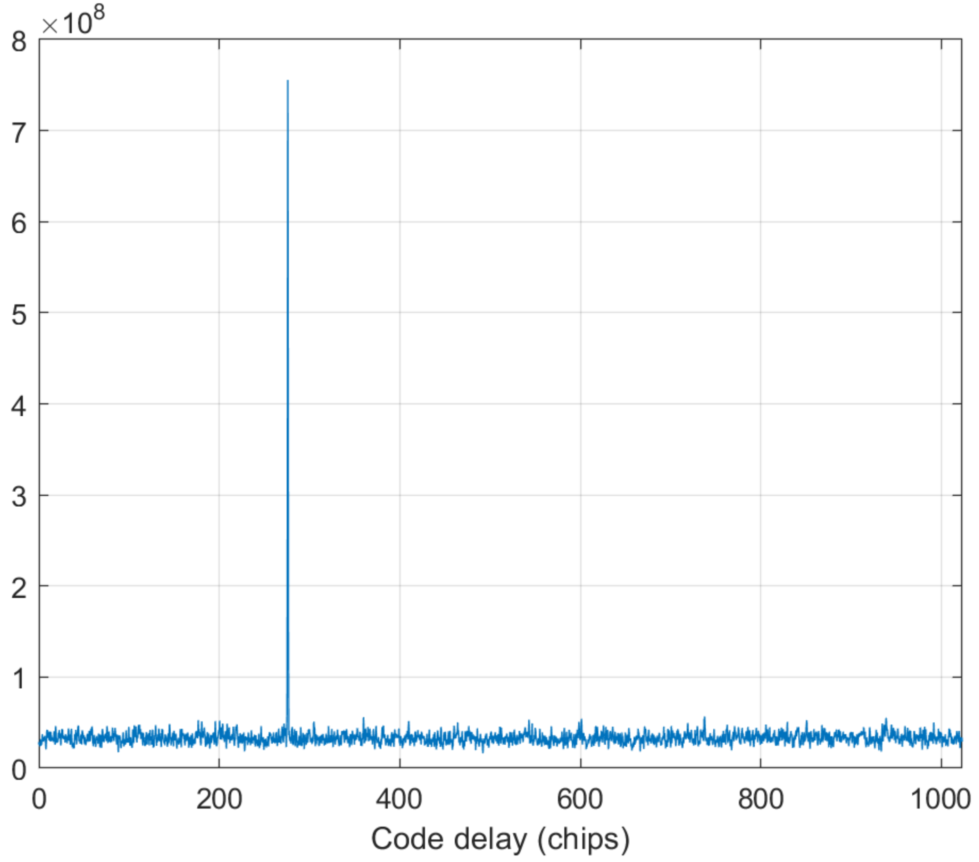
Depends on the relative movement (velocity) of the transmitter and receiver. The Doppler shifted frequency

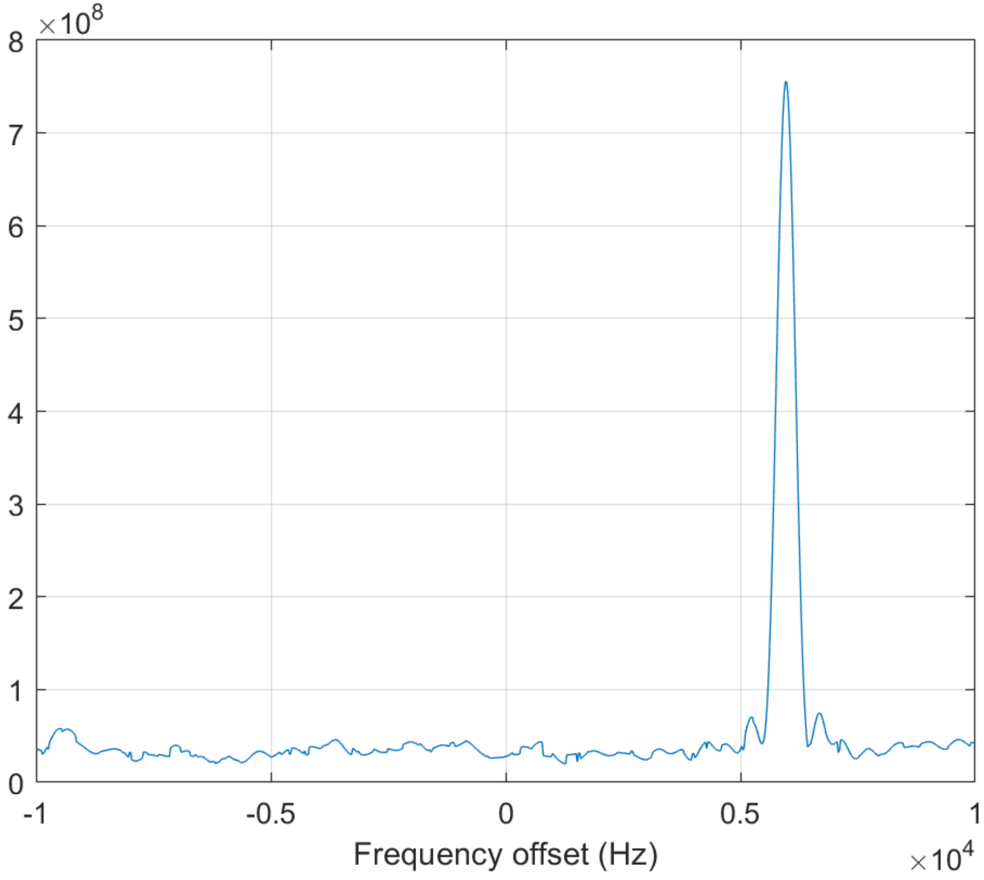
$$f' = f_0 \frac{1}{1 + \frac{v}{c}}$$

Where v is the relative line of sight velocity between the transmitter and receiver, c is the speed of light, f_0 is the signal

Finding the signal in delay and Doppler

GPS
Λ ( )

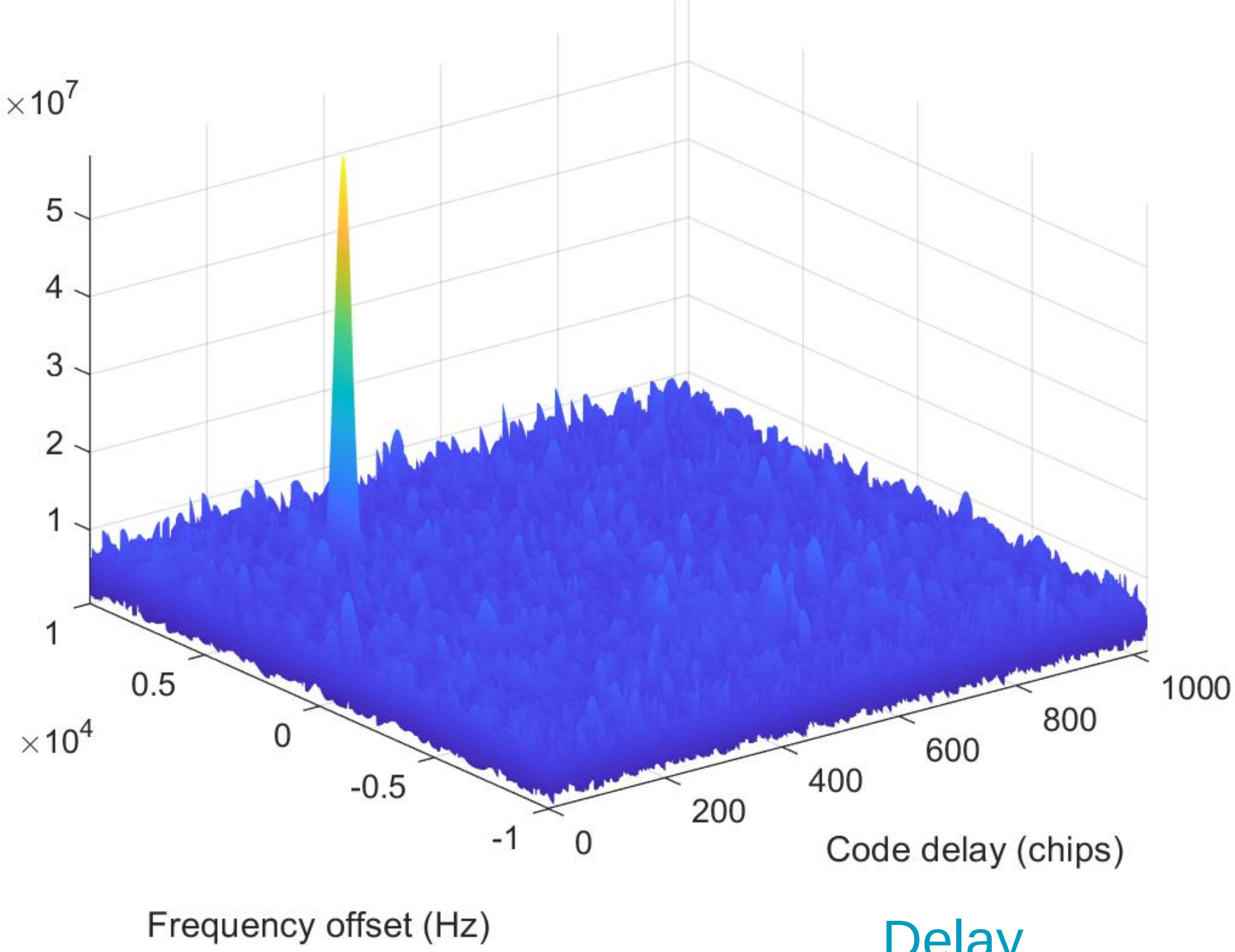




$-\frac{1}{T}$ $\frac{1}{T}$

T – Integration time (1 ms here)

Receiver search space

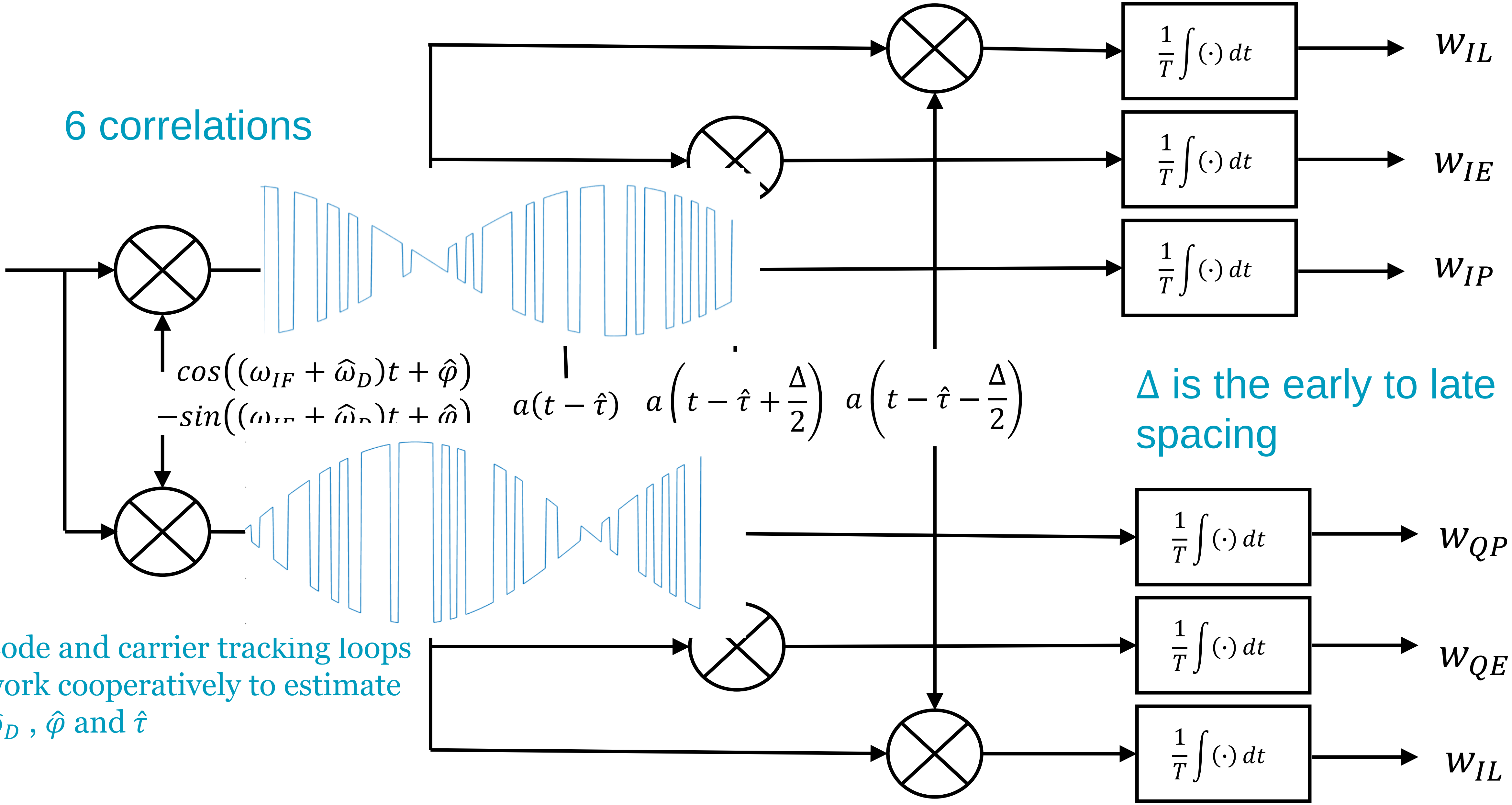


Delay

Doppler

BPSK tracking channel structure

6 correlations



Δ is the early to late spacing

Code and carrier tracking loops work cooperatively to estimate $\hat{\omega}_D$, $\hat{\varphi}$ and $\hat{\tau}$

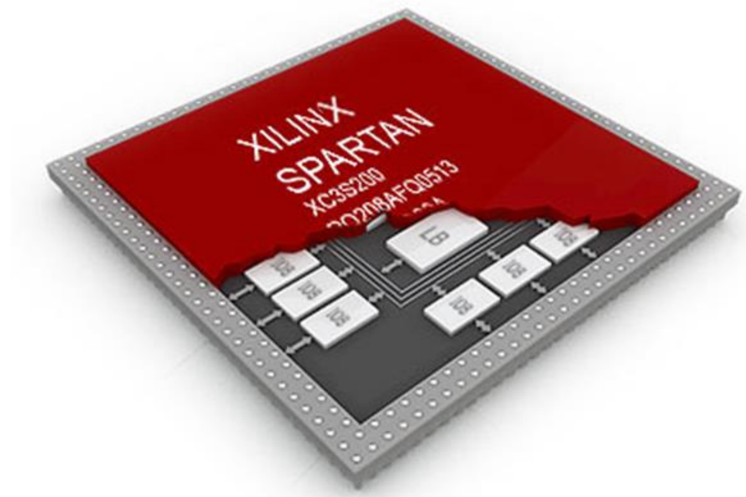
Signal processing hardware

Many **parallel processes** - can be done in software not very efficient

Requires **dedicated memory**, fast multipliers, DMA transfers.

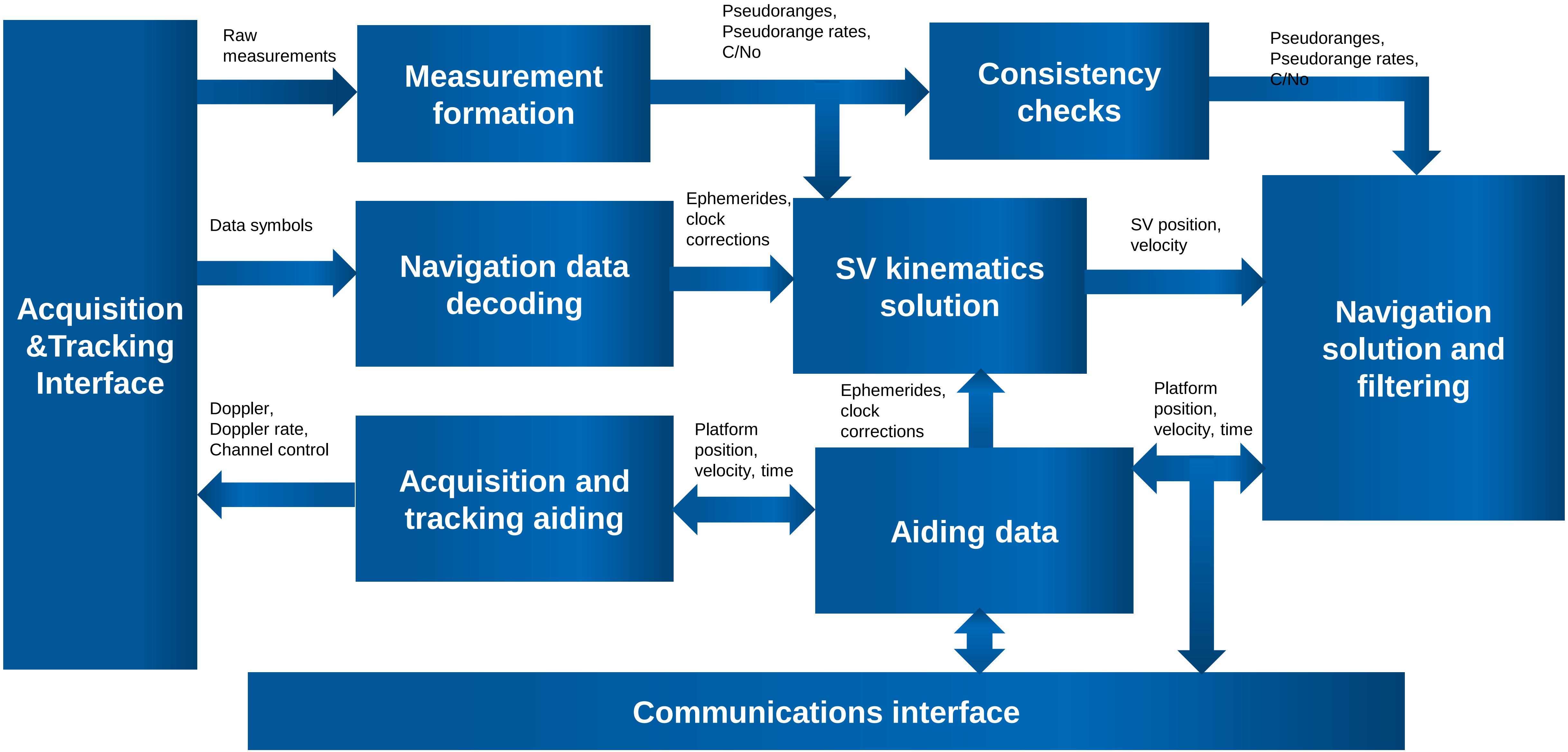
Generally prototyped on Field Programmable Gate Arrays (**FPGAs**)

- FPGA can be suitable for low volume receivers
  - Space receivers
  - Professional market
- **ASICs** are produced for **mass-market** applications
  - Integrating RF section, signal processing and navigation processing



Control software runs relative **simple calculations** but needs a **fast response time** (ms level) and efficient interface to service channels

Navigation processor



Navigation processor

Generally a **hard-core** processor

- Can also be used for acquisition & tracking control software
  - ➢ Requires careful real-time operating system (**RTOS**) design or **dual core**

- Complex **navigation algorithms**, filters and conversions
  - Requires double precision floating point unit
  - Complexity increasing (more processing required)
    - ➢ Increasing number of observations (multi-constellations)
    - ➢ Integration with other sensors
    - ➢ More aiding interfaces (e.g. for enabling Precise Point Positioning (PPP), cm level accuracy)

GNSS receiver output formats

Internally its all calculated in referenced to the center of the earth

ECEF xyz position and velocity

Receiver software will then convert to Lat, Long, Height and out in common formats

- **NMEA sentences** – simple ASCII strings with different identifiers for different packets
- **RINEX** - Receiver Independent Exchange Format (RINEX) is a data exchange format for raw satellite data among different types of receivers

In addition, each receiver will provide more detailed information in their own packet format

Geometry, dual frequency and differential GNSS

Atmospheric effects

$$\varepsilon^{IONO} = \frac{1}{sin\theta}\frac{40.3TEC}{f^2}$$

Typical errors:

Troposphere ~ 0.5 m

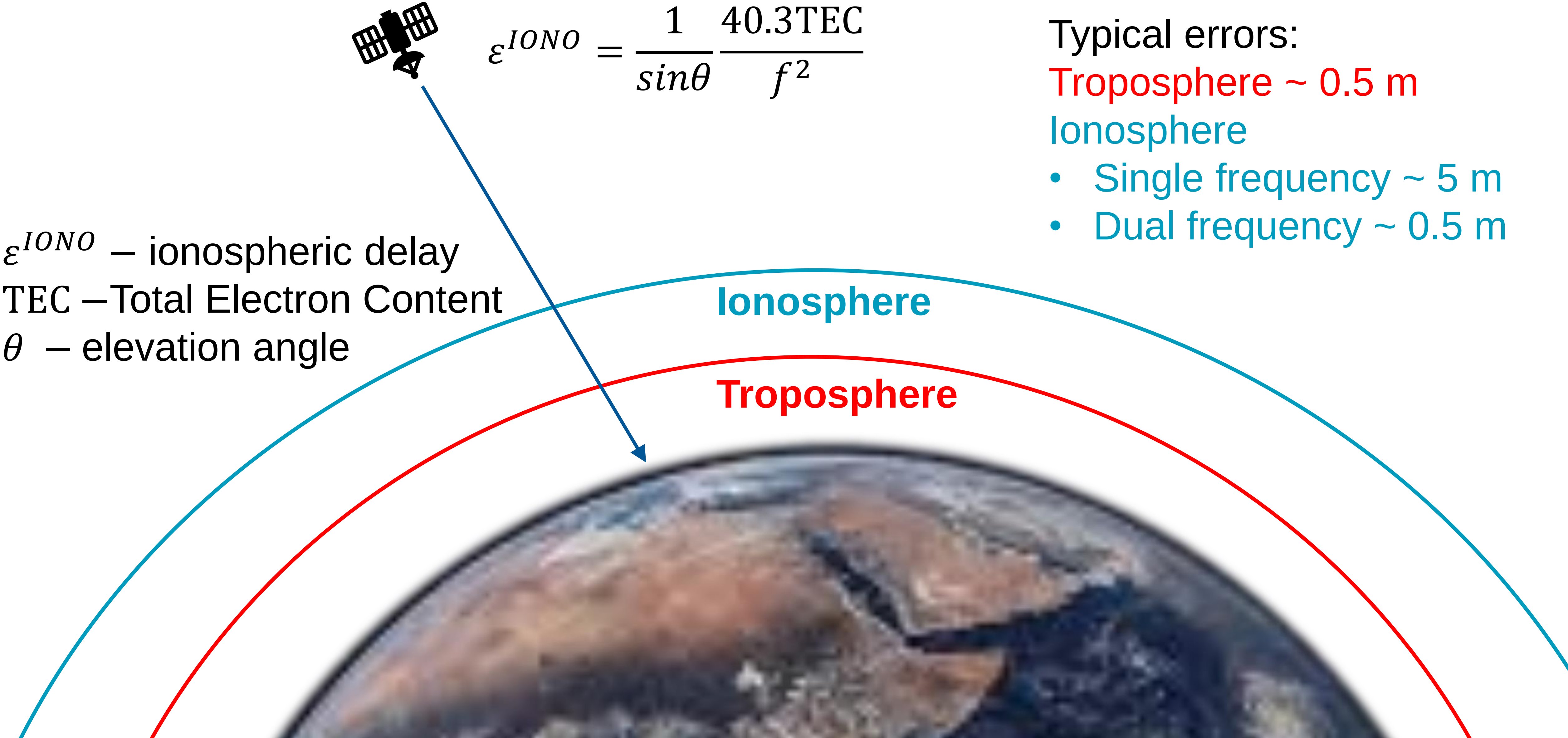
Ionosphere

- Single frequency ~ 5 m
- Dual frequency ~ 0.5 m

ε^{IONO} – ionospheric delay

TEC –Total Electron Content

θ – elevation angle



Error Contributors to range measurements

Error source	Bias error	Random error	RSS
Satellite orbit (ephemeris)	0.8	0.1	0.81
Satellite clock	0.5	0.3	0.58
Ionosphere	4	0.3	4.01
Troposphere	0.2	0.2	0.28
Multipath	1.5	0.3	1.53
Receiver noise	0.2	0.5	0.54
Total range error	4.38	0.75	4.45

Some typical numbers – Ionosphere and multipath particularly have significant variation

Error Contributors to range measurements (Dual Frequency)

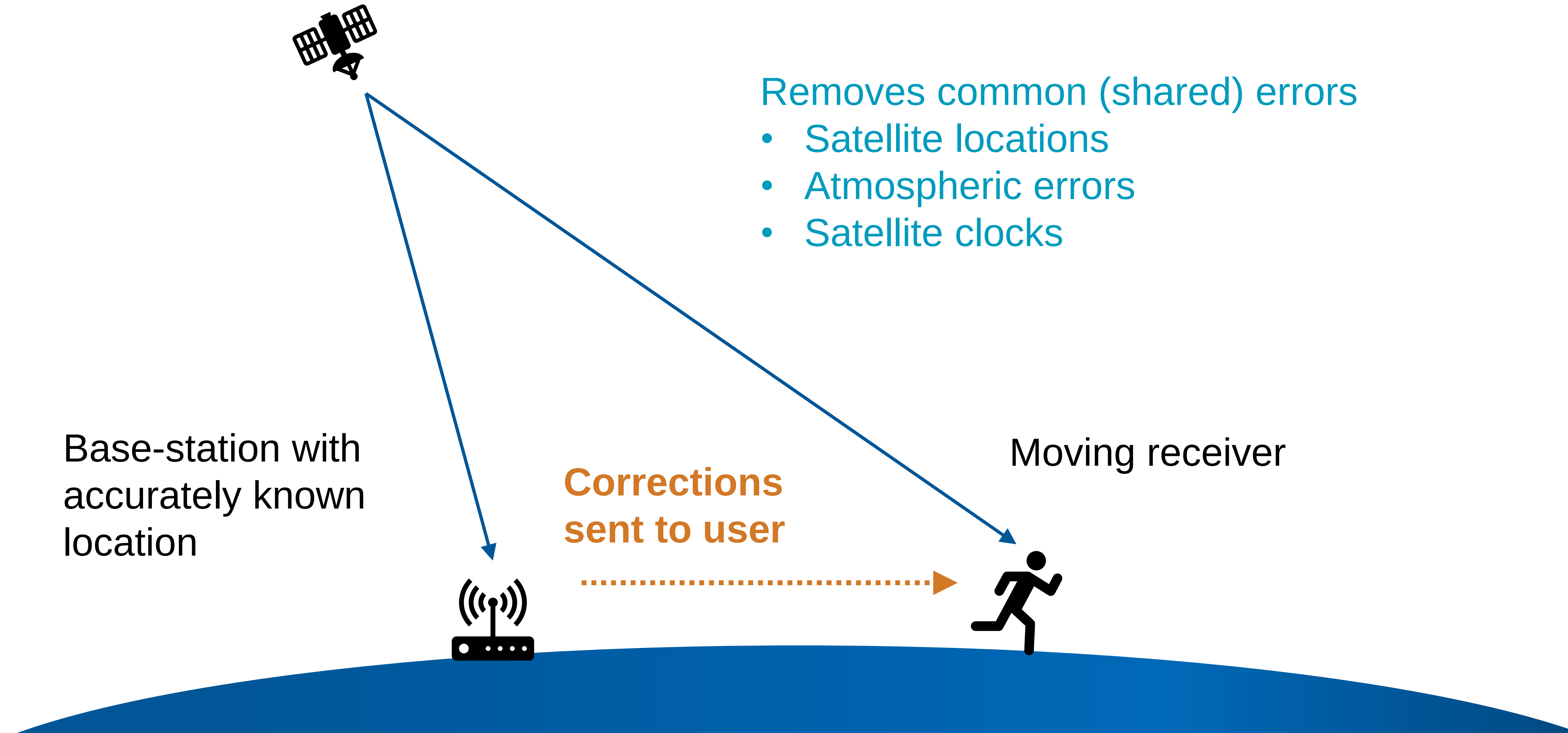
Error source	Bias error	Random error	RSS
Satellite orbit (ephemeris)	0.8	0.1	0.81
Satellite clock	0.5	0.3	0.58
Ionosphere	0.2	0.3	0.36
Troposphere	0.2	0.2	0.28
Multipath	1.5	0.3	1.53
Receiver noise	0.2	0.5	0.54
Total range error	1.81	0.75	1.96

Some typical numbers – Ionosphere and multipath particularly have significant variation

Differential GNSS

Removes common (shared) errors

- Satellite locations
- Atmospheric errors
- Satellite clocks

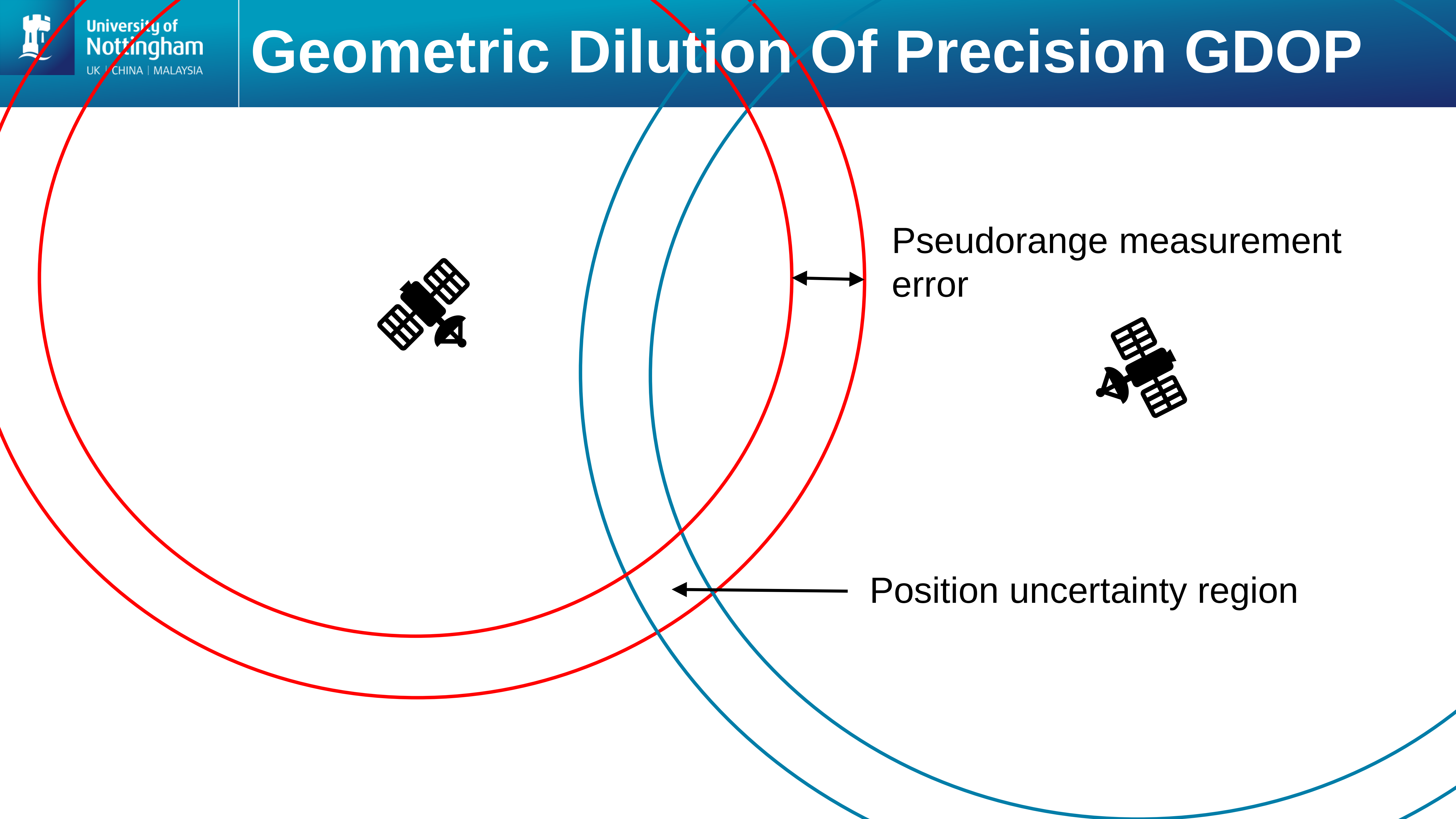


Error Contributors to range measurements (DGPS)

Error source	Bias error	Random error	RSS
Satellite orbit (ephemeris)	0	0.1	0.10
Satellite clock	0.2	0.3	0.36
Ionosphere	0	0.3	0.30
Troposphere	0	0.2	0.20
Multipath	0.2	0.3	0.36
Receiver noise	0.2	0.5	0.54
Total range error	0.35	0.75	0.83

DGPS eliminates common biases
Wide bandwidth receiver / better antenna reduce multipath
Averaging will improve random errors

Geometric Dilution Of Precision GDOP



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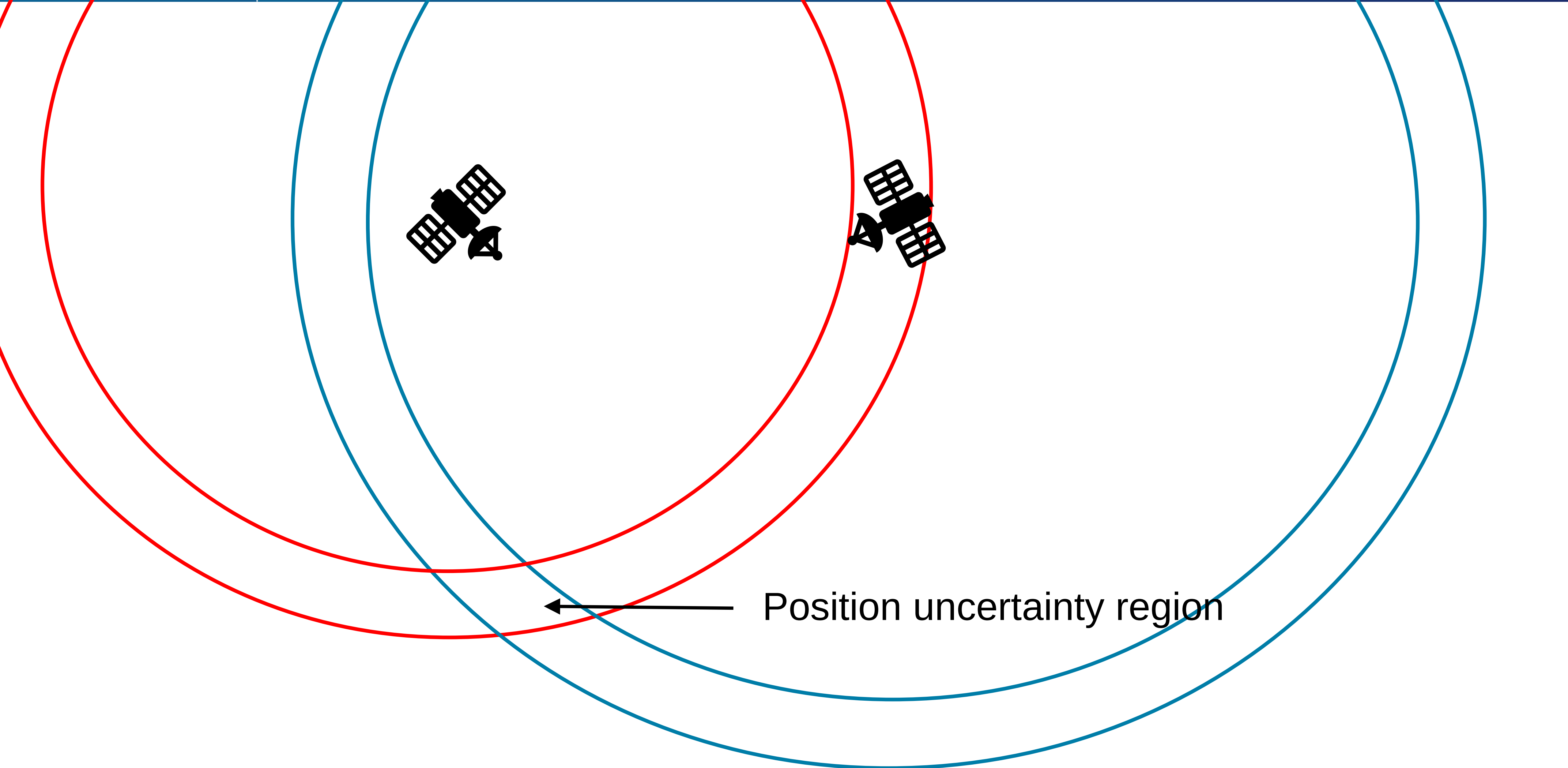

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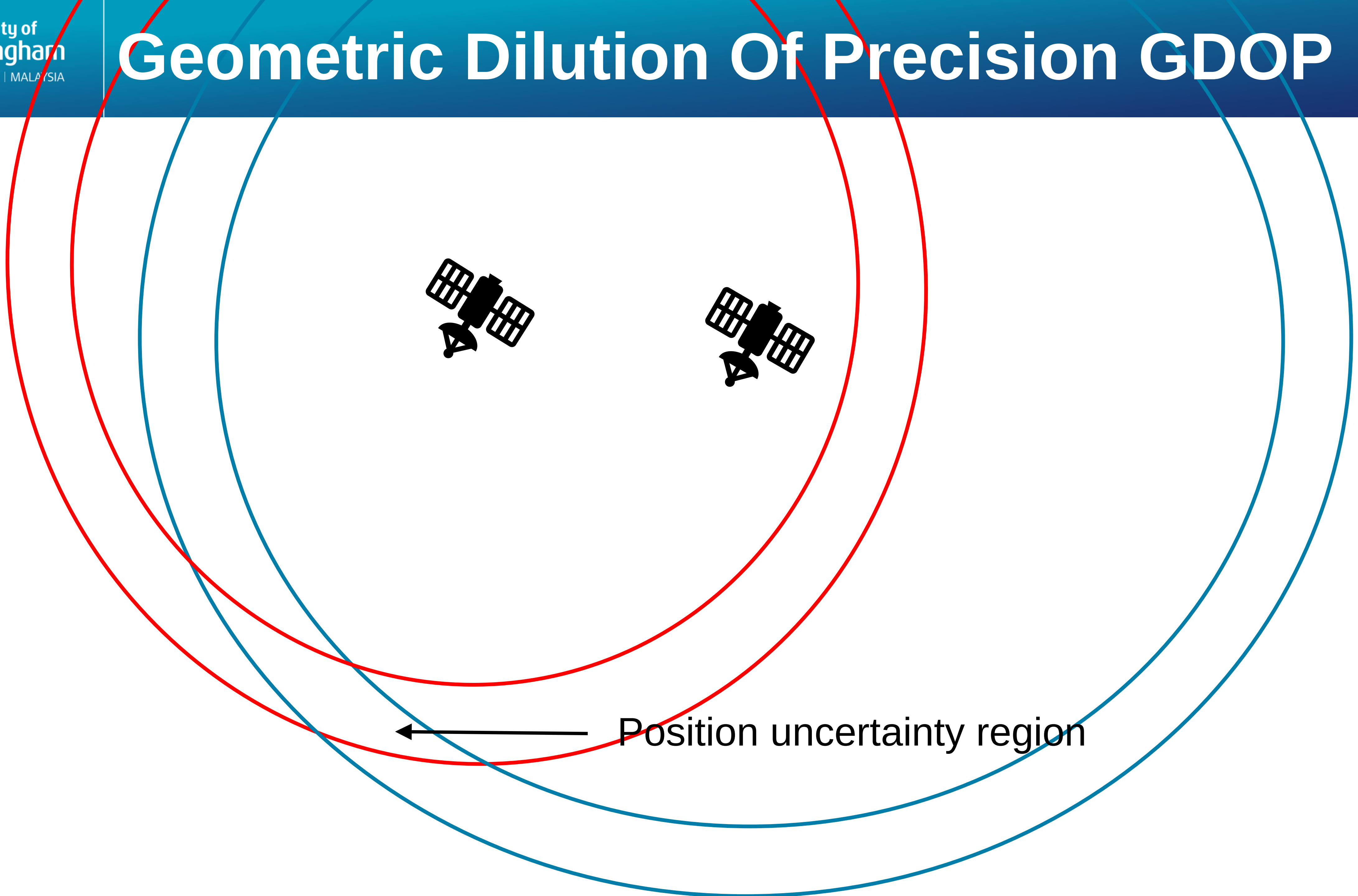

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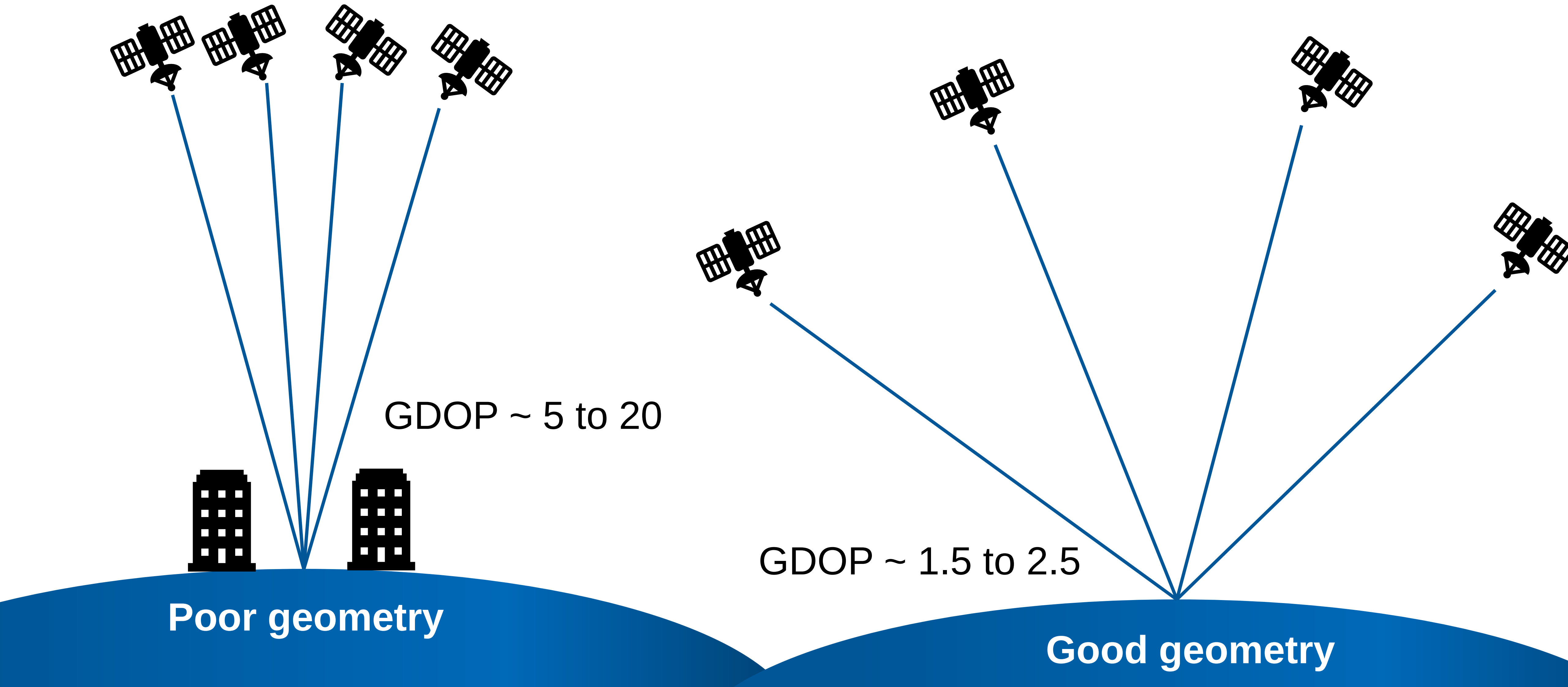

Error Contributors to range measurements

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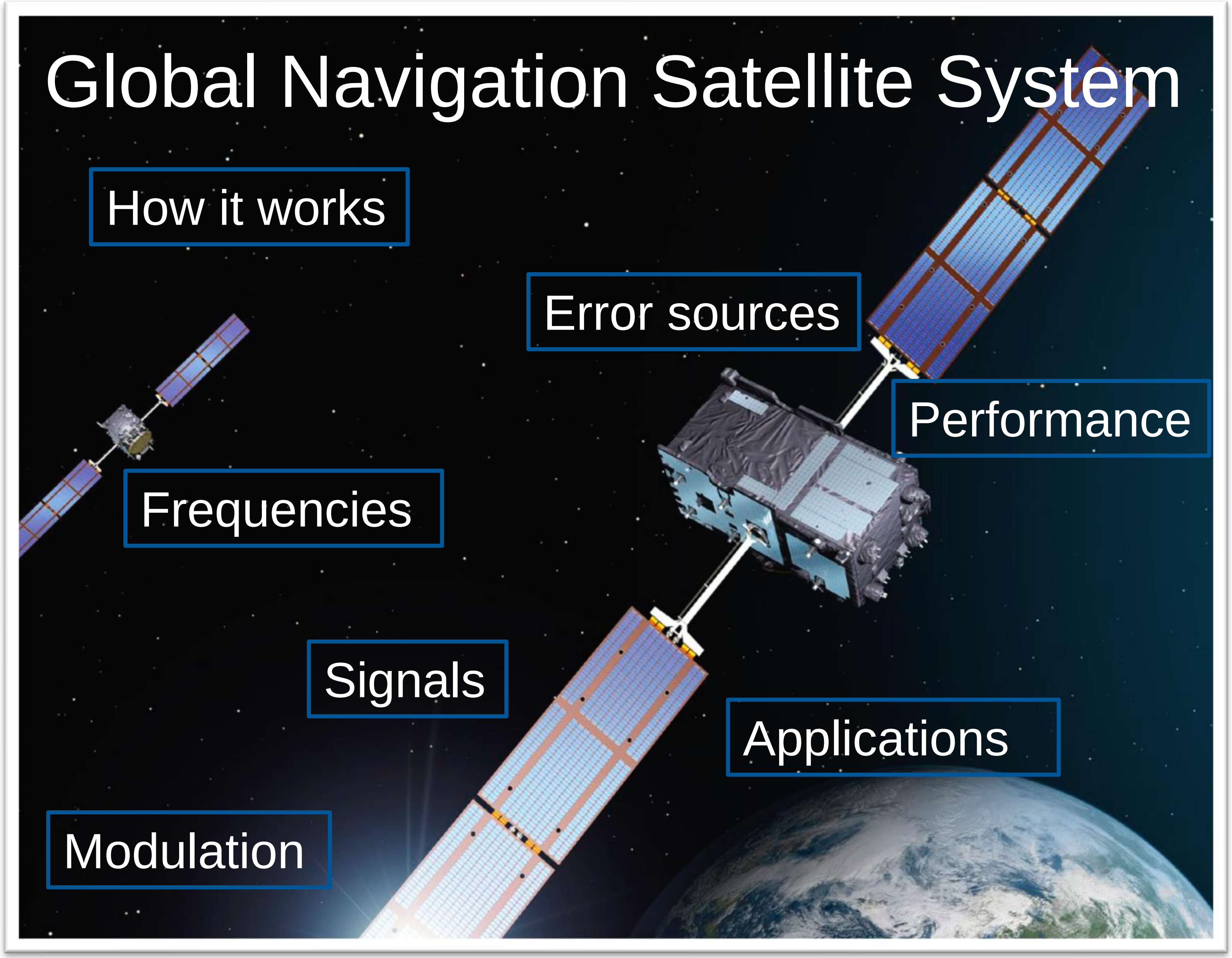
Multipath	1.5	0.3	1.53
Receiver noise	0.2	0.5	0.54
Total range error	4.38	0.75	4.45
GDOP			2.0
3D positioning error			9.9

GNSS errors (and mitigation)

- **Satellite position knowledge** – mitigated with precise orbit modelling
- **Ionospheric propagation delay** – mitigated with a dual frequency receiver, modelling for single frequency, or differential positioning.
- **Tropospheric delay** – mitigated with precise modelling or differential positioning
- **Tracking errors (from noise and interference)** – noise mitigated with strong signals or long averaging times
- **Tracking errors (platform movement)** – dynamic errors mitigated by increasing tracking loop bandwidth (speed of response) or integration with inertial sensors
- **Multipath** – mitigated with a high bandwidth (chipping rate) signal and high bandwidth receiver (narrow correlators)
- **Blockage and attenuation** – Not an error in itself but attenuation with increase tracking errors (jitter) and blockage with cause signal fluctuations and loss

GNSS


Global Navigation Satellite System
How it works
Error sources
Performance
Frequencies
Signals
Applications
Modulation